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Mapping Automotive Like Controls to a General Aviation Aircraft

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MAPPING AUTOMOTIVE LIKE CONTROLS TO A GENERAL AVIATION AIRCRAFT

by

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Richard "Pat" Anderson, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Mechanical Engineering Department and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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ABSTRACT

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The purpose of this thesis was to develop fly-by-wire control laws enabling a general aviation aircraft to be flown with automotive controls, i.e. a steering wheel and gas/brake pedals. There was a six speed shifter used to change the flight mode of the aircraft. This essentially allows the pilot to have control over different aspects of the flight profile such as climb/descend or cruise. A highway in the sky was used to aid in the navigation since it is not intuitive to people without flight experience how to navigate from the sky or when to climb and descend.

Many believe that general aviation could become as widespread as the automobile. Every person could have a personal aircraft at their disposal and it would be as easy to operate as driving an automobile. The goal of this thesis is to fuse the ease of drivability of a car with flight of a small general aviation aircraft. A standard automotive control hardware setup coupled with variably autonomous control laws will allow new pilots to fly a plane as easily as driving a car. The idea is that new pilots will require very little training to become proficient with these controls. Pilots with little time to stay current can maintain their skills simply by driving a car which is typically a daily activity. A human factors study was conducted to determine the feasibility of the applied control techniques. Pilot performance metrics were developed to compare candidates with no aviation background and experienced pilots. After analyzing the relative performance between pilots and non-pilots, it has been determined that the control system is robust and easy to learn. Candidates with no aviation experience whatsoever can learn to fly an aircraft as safely and efficiently as someone with hundreds of hours of flight experience using these controls.

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LIST OF ACRONYMS

AGATE	Advanced General Aviation Transport Experiments
AOA	Angle of Attack
AOS	Angle of Sideslip
CAA	Civil Aeronautics Administration
CAS	Calibrated Airspeed
CFR	Code of Federal Regulations
DOF	Degrees of Freedom
ERAU	Embry-Riddle Aeronautical University
ERCO	Engineering and Research Corporation
FAA	Federal Aviation Administration
FMS	Flight Management System
GA	General Aviation
GPS	Global Positioning System
HF	Human Factors
HFCS	Haptic Flight Control System
HITS	Highway in the Sky
IFR	Instrument Flight Rules
ILS	Instrument Landing System
LQR	Linear Quadratic Regulation
MAP	Manifold Air Pressure
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NP	Non-Pilot
PI	Proportional, Integral
PID	Proportional, Integral, Derivative
RPM	Rotations per Minute
SP	Student Pilot
SUS	System Usability Scale
TAS	True Airspeed
UAV	Unmanned Aerial Vehicle
VFR	Visual Flight Rules
V/S	Vertical Speed
WRT	With Respect to
XP	Experienced Pilot

NOMENCLATURE

α	Angle of Attack
β	Angle of Sideslip
$\bar{c}$	Mean Aerodynamic Chord (wing)
A_x	Linear acceleration along X-axis
A_y	Linear acceleration along Y-axis
A_z	Linear acceleration along Z-axis
p	Angular rate about X-axis
q	Angular rate about Y-axis
r	Angular rate about Z-axis
u	Linear wind velocity along X-axis
v	Linear wind velocity along Y-axis
w	Linear wind velocity along Z-axis
N	Position North relative to starting point
E	Position East relative to starting point
h	Altitude
$\dot{N}$	Northward velocity
$\dot{E}$	Eastward velocity
$\dot{h}$	Vertical velocity
J_x	Mass moment of inertia about X axis
J_{xz}	Mass moment of inertia about XZ plane
J_y	Mass moment of inertia about Y axis
J_z	Mass moment of inertia about Z axis
S_w	wing area
δ_e	Elevator deflection
δ_a	Aileron deflection
δ_r	Rudder deflection
θ	Pitch attitude with respect to horizon
Φ	Roll attitude with respect to horizon
Ψ	Heading attitude with respect to North (clockwise)
C_L	Coefficient of lift
C_D	Coefficient of drag
C_Y	Coefficient of side force
C_m	Pitching moment coefficient
C_l	Rolling moment coefficient
C_N	Yawing moment Coefficient

STABILITY DERIVATIVE DEFINITIONS

C_{L_α}	Lift curve slope
C_{L_q}	Change of coefficient of lift WRT pitch rate
$C_{L_{\delta e}}$	Change of coefficient of lift WRT elevator deflection
C_{L_0}	Coefficient of lift at zero AOA
$C_{D_{\alpha 2}}$	Change in coefficient of drag WRT α^2
C_{D_0}	Coefficient of drag at zero AOA
C_{m_α}	Longitudinal stability
$C_{m_{\delta e}}$	Elevator control power
$C_{m_{\dot{\alpha}}}$	Change in pitching moment coefficient WRT $\dot{\alpha}$
C_{m_q}	Pitch damping
C_{Y_β}	Change in side force WRT AOS
$C_{Y_{\delta r}}$	Change in side force WRT rudder deflection
C_{l_β}	Dihedral effect
C_{l_p}	Roll damping
C_{l_r}	Change in rolling moment coefficient WRT yaw rate
$C_{l_{\delta a}}$	Aileron control power
$C_{l_{\delta r}}$	Change in rolling moment coefficient WRT rudder deflection
C_{N_β}	Directional Stability (aka Weather vane stability)
C_{N_p}	Change in yawing moment coefficient WRT roll rate
C_{N_r}	Yaw damping
$C_{N_{\delta a}}$	Adverse yaw
$C_{N_{\delta r}}$	Rudder control power

1. INTRODUCTION

The purpose of this thesis was to develop fly-by-wire control laws to enable the flight of a general aviation aircraft using only automotive controls. It is difficult for pilots to stay current or maintain their pilot skills if they only are able to fly sporadically. This control setup will allow pilots who only plan on flying once or twice a month for utility rather than pleasure or profession to maintain their flight skills simply while driving their cars on a daily basis. A version of synthetic vision using follow-me boxes, better known as a highway in the sky was used to assist in the navigation from one airport to another since it is not obvious how to navigate and plan descents without extensive training as a pilot. A brief history of the development of the highway in the sky concept and motivation for the development of this control system is provided in the following subsection.

1.1. History and Motivation

1.1.1. General Aviation and Personal Aircraft

Since the advent of manned flight, it has been envisioned that one day it would be commonplace that anyone could take to the sky in a personal air vehicle to go to work or make a quick trip to a city that is too far to travel by car in a reasonable amount of time. In 1934, the assistant chief of aeronautics for the National Advisory Committee for Aeronautics (NACA), Fred Weick, began working on an aircraft based on the 1931 Stout Skycar. He wanted to use fabric covering instead of aluminum to make it lighter and more affordable. He also made control modifications based on NACA research. Weick removed the use of rudder pedals and coupled the rudder to the ailerons for the purpose of coordinated turns. Weick's new aircraft was dubbed the W-1; it featured tricycle landing gear with a steerable nose wheel, a parasol wing, and a pusher prop. Most of the modifications and construction were made out of his own pocket so in 1936, he left NACA and joined the Engineering and Research Corporation (ERCO) as the chief designer of the aircraft team to continue working on his design. His design efforts were focused on the safety and simplicity of the W-1. His goal was to produce an affordable aircraft that would not stall or spin. [1]

The next version of the aircraft, dubbed the ERCO 310, had a low-wing, tractor-prop configuration. Its first flight was made in October 1937 at College Park Airport and was renamed the "Ercoupe." The engine used was the ERCO I-L 116 which was replaced by the more affordable Continental A-65 horizontal. Since there were no rudder pedals, it was flown using only the control wheel. It was considered a two-control aircraft since the control wheel only affected pitch and roll with the rudder coupled to the ailerons for coordinated turns. The control wheel also steered the nose wheel on the ground like an automobile. From the Ercoupe's Wikipedia page, "*A completely new category of pilot's license was created by the CAA for Ercoupe pilots who had never used a rudder pedal. The Ercoupe was certified by the Civil Aeronautics Administration (CAA) as 'characteristically incapable of spinning.'*" [1] The idea was to open up general aviation to a broader class of people: people who wouldn't need extensive training in order to fly this plane. It was said by LIFE magazine that the Ercoupe was foolproof. It was showcased with a pilot landing the Ercoupe with his hands in the air. [1]

The two-seat version of the Ercoupe, model 415, began production in 1940. However, World War II halted all civil aircraft production by redirecting all aluminum for wartime production efforts. ERCO began production on a wooden version of the Ercoupe for military use. By 1946, after the war, production of the Ercoupe model 415-C resumed. Over 4,000 aircraft were produced and sold for $2,665 in 1946 alone. During maximum production, ERCO was able to produce 34 Ercoupes per day working around the clock. General aviation began its decline in the late 1940s. From 1947 to 1950, only 213 aircraft were sold. ERCO sold its inventory to Sanders Aviation and the dream of everyone in America owning their own Ercoupe for personal use faded. Many different aircraft manufacturers made different versions of the Ercoupe holding to the two-control operation design including Forney, Alon, and ending with the Mooney M-10 Cadet in 1970. Sales of general aviation aircraft would not be comparable to what they were in 1946 until the mid ‘90s, during which time there was much development in the technologies leading to the possibility of widespread general aviation with little required training for new pilots. [1]

It is clear that it may be possible for the Federal Aviation Administration (FAA) to create a new license category similar to what the CAA created for the Ercoupe. The control configuration of this aircraft will be so similar to that of an automobile that previous knowledge of flight is not required at all. The use of driving skills that about every American has is all that is required to fly an aircraft with this configuration and control laws. The goal is to facilitate widespread general aviation aircraft for flights that are too far to travel by car in a day, but too short to want to use the commercial airlines. The dream of “flying cars” or simply an aircraft in everyone’s driveway may still yet be realized and there are many contributing factors that will pave the way. These developments have started in the 1950s and even today the government, industry, and academia are making strides toward making it happen.

1.1.2. Development of the Highway in the Sky

The design and development of tools that aid human perception to reduce required flight skills has been of special interest in recent years. In the mid '90s ending in 2001, the National Aeronautics and Space Administration (NASA) created a program called the Advanced General Aviation Transport Experiments (AGATE). A consortium consisting of NASA, the FAA, numerous general aviation industry partners, and universities, with a $52 million budget attempted to implement a maneuver guidance system or "Highway in the Sky," without widespread success. The expectation was to facilitate the transition to a "Highway in the Sky," by exploiting existing skills and habits found in everyday life, i.e. driving. Quoted from a NASA press release on affordable alternative transportation in July 1996, "*The purpose of AGATE is to enable market growth for inter-city transportation in small aircraft. AGATE aims to make single-pilot, light airplanes more safe, affordable and available as a viable part of the nation's transportation system. AGATE targets trips of 150 to 700 miles – round trips that are too far to complete in a day and too short to efficiently use the hub-and-spoke system.*" [2]

These efforts stem back as far as the mid '50s. Civil and military researchers showed interest with the military leading the researching efforts. The Navy's George W. Hoover pioneered the concept of the "Highway in the Sky." Although much research was done in this area, industry showed little interest so it did not blossom. NASA's Langley Research Center in Hampton, VA conducted conceptual research for a pathway-in-the-sky in the 1970s. In the '80s, Langley's research efforts focused on actual problems plaguing flight at the time, i.e. poor visibility leading to inadvertent loss of control for typical general aviation IFR pilots. This sparked the start of a program headed by John D. Shaughnessy and Hugh P. Bergeron called the Single Pilot IFR (SPIFR) project. It used piloted simulations and flight tests in order to highlight the difficulties in maintaining situational awareness for inexperienced pilots during IFR flight. A concept known as the "follow-me box," became popular and drastically increased the performance of the inexperienced pilots. This follow-me box used simplified rectangular lines to form a guidance box to be followed by the pilot projected onto a display. [3]

The follow-me box concept was further developed by Eric C. Stewart while performing similar experiments. Stewart refined the concept to resemble an actual highway in the sky such that it seemed to the naked eye like driving a car down the road. This research was conducted under Langley's "E-Z Fly," program. Many subjects flew a simulation using Stewart's highway in the sky including those without any piloting experience whatsoever. "*Results obtained with the display were remarkable, with significant improvements in pilot guidance and response. In fact, individuals with no exposure to pilot skills were able to rapidly adapt to the guidance system and successfully fly full operational missions. Despite the significant improvement observed in pilot performance, the fact that the concept was directed at the general aviation community's low end, where computational requirements and costs were immediate barriers, stifled further research.*" [3] Thusly, Hoover's "Highway in the Sky," would have to wait for the relevant technologies to catch up.

This leads to the AGATE program which started in the mid '90s. AGATE members wanted to further develop the pathway-in-the-sky concept taking cues from the industry's movement toward a similar system. Their goal was to enhance its viability and reduce the cost of a system capable of providing the pathway-in-the-sky for any aviation application. In 1998, contracts were awarded to AvroTec Corporation and later to Avidyne to develop the HITS display system. By July 2000, there was an operational system that was installed on a Lancair Columbia aircraft which was later successfully demonstrated at the EAA AirVenture 2001 airshow in Oshkosh, Wisconsin. The AGATE program ended in 2001 due to no further funding and the HITS display system was never put into production. Figure 1 shows NASA's vision for their highway in the sky in an artist's rendition. [3]

FIGURE 1: NASA AGATE HIGHWAY-IN-THE-SKY CONCEPT

1.1.3. Current Developments Paving the Way

There have been other developments in the general aviation field researched at NASA Langley by Paul Schutte and Kenneth Goodrich called the Naturalistic Flight Deck employing a method called the Haptic Flight Control System (HFCS). There has been an evaluation of the HFCS involving twenty-four instrument-rated pilots in which four different fictitious flights were planned and flown using a desktop simulation. It was found that the HFCS improved situational awareness, appropriate pilot workload, and improved pilot acceptance. Each mission was flown in three different ways: manual control, fully automated control, and a simplified version of the HFCS. It was found that the HFCS provided a significant advantage to the pilots in a number of statistically and non-statistically significant results. [4, 5]

Currently, large commercial aircraft are highly automated and the pilot has three main ways of controlling the aircraft. These are direct control using the stick, rudder, and throttle, autopilot control is used to control certain states such as airspeed, heading, altitude, or rate of climb/descent, and the flight management system (FMS) which can control earth-referenced features such as depart an airport, fly to a waypoint, and land at another airport. Any one of the three or a combination of all three can be used to operate the aircraft at any time. Given the limitations of any human, this can be confusing and can ultimately lead to pilot error. The Haptic-Multimodal Flight Control System is a single flight control system that can utilize all three of these methods in a single intuitive interface. [6, 7]

With the HFCS, the pilot issues commands to the aircraft solely through the stick and throttle. The exact methods used by the HFCS are not relevant to the development of the control laws used in this thesis, but the philosophy and motivation behind the human/machine interaction and levels of autonomy are very relevant. As outlined by Schutte, et al, 2012, "*…the automation will not fly the entire route rather the pilot has to make all coarse turns and altitude changes… the pilot must be in the loop whenever major changes in the aircraft's trajectory are made. This lack of preprogramming provides a benefit from a human factors perspective. Humans become complacent with reasonably reliable pre-programmed automation. But one of their primary roles is to monitor the mission progress and the automation. In order to effectively monitor over long durations they need to be engaged in the task at regular intervals.*" [8]

The previous statement is largely the underlying motivation for mapping automotive like controls to flight of an aircraft. It is possible with today's technology that the aircraft could be flown entirely automated and the pilot would simply have to input where he/she wants to the plane to go and what time to arrive into the FMS and the computer would take care of the rest. There is a term for this: "automation addiction." [10] Automation addiction is when the level of engagement between the human and the aircraft is minimized by the computer. In other words, if the pilot delegates too much or all of the control and decision making to the computer then over time, there is a weakening in their effectiveness to respond to unexpected scenarios or emergencies. If a failure were to present itself, it would be difficult for the pilot to react quickly if necessary. It is paramount that the pilot remain in the loop enough that their situational awareness is not compromised. [9, 10]

Rather than develop new technologies, the use of existing technology in a novel fashion presents itself to be a more viable solution. In previous years, fly-by-wire systems in small general aviation aircraft were infeasible due to weight restrictions on computers, actuators, and redundant systems to mitigate any possible failures. Recent advancements of electro-mechanical systems are paving the way for use of fly-by-wire systems in general aviation without being detrimental to useful payload. Diamond's 4-axis fly-by-wire DA-42 is a prime example of state-of-the-art components used for active electronic control of the aircraft. Advancements in computer technology will allow redundant systems to become more substantial in the miniaturizing of processors. Currently, the DA-42 uses a processor measuring 5 by 10 inches which will reduce in the coming years to allow for more redundant or lighter systems.

Of course, it is difficult and expensive to get any new aircraft or technology certified due to FAA regulations. The Small Airplane Revitalization Act of 2013 will be game changing if passed. This act passed the Senate on October 4th, 2013 and is awaiting House approval. This act mandates that the FAA shall "*create a regulatory regime for small airplanes that will improve safety and decrease certification costs*" under CFR part 23. It also states that the FAA shall "*replace current, prescriptive requirements contained in FAA rules with performance-based regulations*." [11] The average age of small GA aircraft on the market today is 40 years old. This act could significantly benefit new technologies with a less costly certification process.

2. SIMULATION ENVIRONMENT

2.1. Basic Aircraft Terminology

Before delving into the discussion of exactly how a general aviation aircraft can be controlled with automotive control hardware, a brief discussion of aircraft terminology is relevant. There are going to be many terms in reference to pitching and rolling motions which are angular velocities. An illustration of these would be beneficial to those unfamiliar with the terminology.

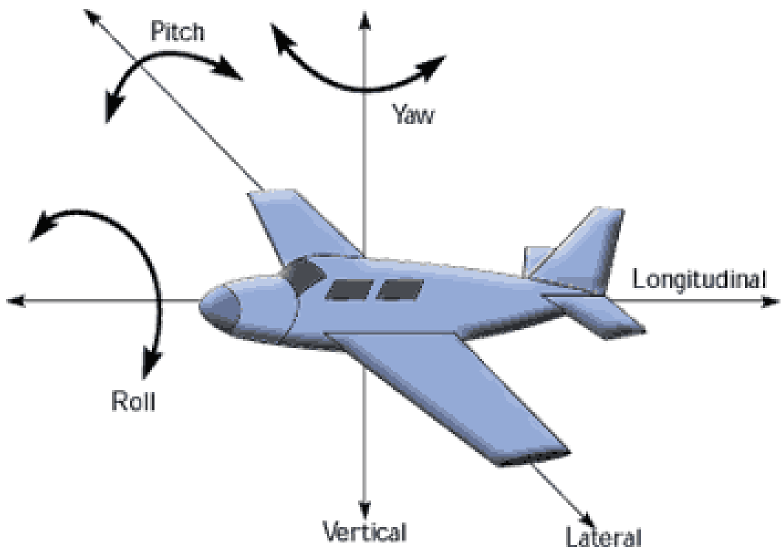


FIGURE 2: AXES OF AN AIRCRAFT

As can be seen in Figure 2, an aircraft has three axes, the lateral, longitudinal, and vertical axes. The angular velocity about the lateral axis is known as pitching which causes the nose of the aircraft to move up or down. The angular velocity about the longitudinal axis is known as rolling (also known as banking) which would cause the aircraft's wing tips to move up or down. The angular velocity about the vertical axis is known as yawing which would cause the aircraft's nose to move left or right. There is of course much more terminology when speaking of the dynamics of flight, however for the purpose of this thesis, the angular velocities should be enough for those who aren't fluent in flight dynamics. The angular velocities about these axes are the basis for the majority of the control laws. For additional aircraft terminology, please refer to the NOMENCLATURE.

2.2. MATLAB/Simulink® Model

The simulation environment was based on MATLAB/Simulink® software. The equations of motion were built up and solved simultaneously using Simulink's ODE4 Runge-Kutta fixed time-step solver using the flight controls as inputs and the aircraft states as outputs. The aerodynamic model used was that of the Ryan Navion. The Navion was developed in the '40s by North American and was expected to be a high seller in the general aviation industry after World War II. The stability derivatives for this aircraft were obtained from *Flight Stability and Automatic Control* by Robert Nelson [12]. The model includes a realistic lift curve in order to test stall protection systems as well as a ground reaction model for takeoff and landing scenarios. The Aerosim block set in Simulink was utilized to obtain the ground reaction blocks. It is a simplified three-point ground reaction of forces and moments. The power plant is modeled after the Lycoming IO-360 reciprocating engine. This engine was chosen because it was flight tested and modeled right here at ERAU with high fidelity. The following figure depicts the Navion for those unfamiliar with the aircraft.

FIGURE 3: IMAGE OF THE RYAN NAVION

The following tables outline the relevant geometric, performance, and stability parameters of the Navion.

TABLE 1: GENERAL PARAMETERS OF THE NAVION

Parameter	Symbol	Value	Units
Wing Span	b	33.4	ft
Wing Area	S_w	180	ft^2
Mean Aerodynamic Chord	$\bar{c}$	5.7	ft
Length	L	27.25	ft
Height	H	8.53	ft
Maximum Gross Takeoff Weight	MTOW	2750	lb_f
Weight used in Simulation	W	2150	lb_f
Mass Moment of Intertia about X-Axis	J_x	1048	slug ft^2
Mass Moment of Intertia about Y-Axis	J_y	3000	slug ft^2
Mass Moment of Intertia about Z-Axis	J_z	3530	slug ft^2
Mass Moment of Inertia about XZ Plane	J_{xz}	0	slug ft^2

TABLE 2: PERFORMANCE CHARACTERISTICS OF THE NAVION

Parameter	Symbol	Value	Units
Never exceed speed	V_{NE}	165	kt
Design Cruise speed	V_{cr}	135	kt
Stall speed (gear and flaps down)	V_{S0}	43	kt
Stall speed (clean configuration)	V_{S1}	56	kt
Service ceiling	-	15,000	ft
Best Rate of Climb	-	1,250	fpm
Wing loading	-	11.4	psf
Power to Mass ration	-	13.4	lb/hp

TABLE 3: STABILITY DERIVATIVES OF THE NAVION FROM NELSON

Parameter	Value	Units
C_{L_α}	4.440	Per rad
C_{L_q}	3.800	Per rad/s
$C_{L_{\delta e}}$	0.355	Per rad
C_{L_0}	0.410	Unitless
$C_{D_{\alpha 2}}$	0.330	Per rad^2
C_{D_0}	0.050	Unitless
C_{m_α}	-0.683	Per rad
$C_{m_{\delta e}}$	-0.923	Per rad
$C_{m_{\dot{\alpha}}}$	-4.36	Per rad/s
C_{m_q}	-9.96	Per rad/s
C_{Y_β}	-0.564	Per rad
$C_{Y_{\delta r}}$	0.157	Per rad
C_{l_β}	-0.074	Per rad
C_{l_p}	-0.410	Per rad/s
C_{l_r}	0.107	Per rad/s
$C_{l_{\delta a}}$	-0.134	Per rad
$C_{l_{\delta r}}$	0.012	Per rad
C_{N_β}	0.071	Per rad
C_{N_p}	-0.0575	Per rad/s
C_{N_r}	-0.125	Per rad/s
$C_{N_{\delta a}}$	-0.0035	Per rad
$C_{N_{\delta r}}$	-0.072	Per rad

Figure 5 displays the highest level of the Simulink model that was created. The blue block contains the flight dynamics equations of motion. The inputs are the flight controls, $\delta a, \delta e, \delta r,$ manifold air pressure (MAP), and RPM, respectively. The outputs are the linear axial accelerations, the angular rates, linear axial wind velocities, Euler angles (θ, Φ, Ψ), position (N, E, h), Earth-relative velocities ($\dot{N}, \dot{E}, \dot{h}$), wind parameters (true airspeed, α, and β), calibrated airspeed (CAS), vertical speed (V/S), the rate of heading change WRT time ($\dot{\Psi}$), ground speed, and a ground contact Boolean. The white block contains the control inputs from the automotive control hardware which were normalized. The outputs are the steering wheel which can go from -1 (left) to 1 (right), the gas and brake pedals are 0 when not pressed and 1 when fully pressed, and the shifter outputs an integer from 1 to 7 in order to select the flight mode. The red block contains the control laws for all seven flight modes which use some or all of the outputs from the flight dynamics block as inputs. The outputs from this block are the flight controls that are input to the flight dynamics block. The yellow blocks are visual aids. The largest of the three takes the outputs from the flight dynamics block to send them via UDP to the machine running Flight Gear in order to visually represent the states of the aircraft. The one below that takes all of the flight parameters in order to display them digitally or on graphs during the testing of the control system. The last one takes the outputs required and displays them on a standard “six pack” of flight instruments shown below in Figure 4. In the top row from left to right are the airspeed indicator, the artificial horizon, and the altimeter. In the bottom row from left to right are the turn coordinator, the heading indicator, and the vertical speed indicator.

FIGURE 4: STANDARD “SIX PACK” OF FLIGHT INSTRUMENTS

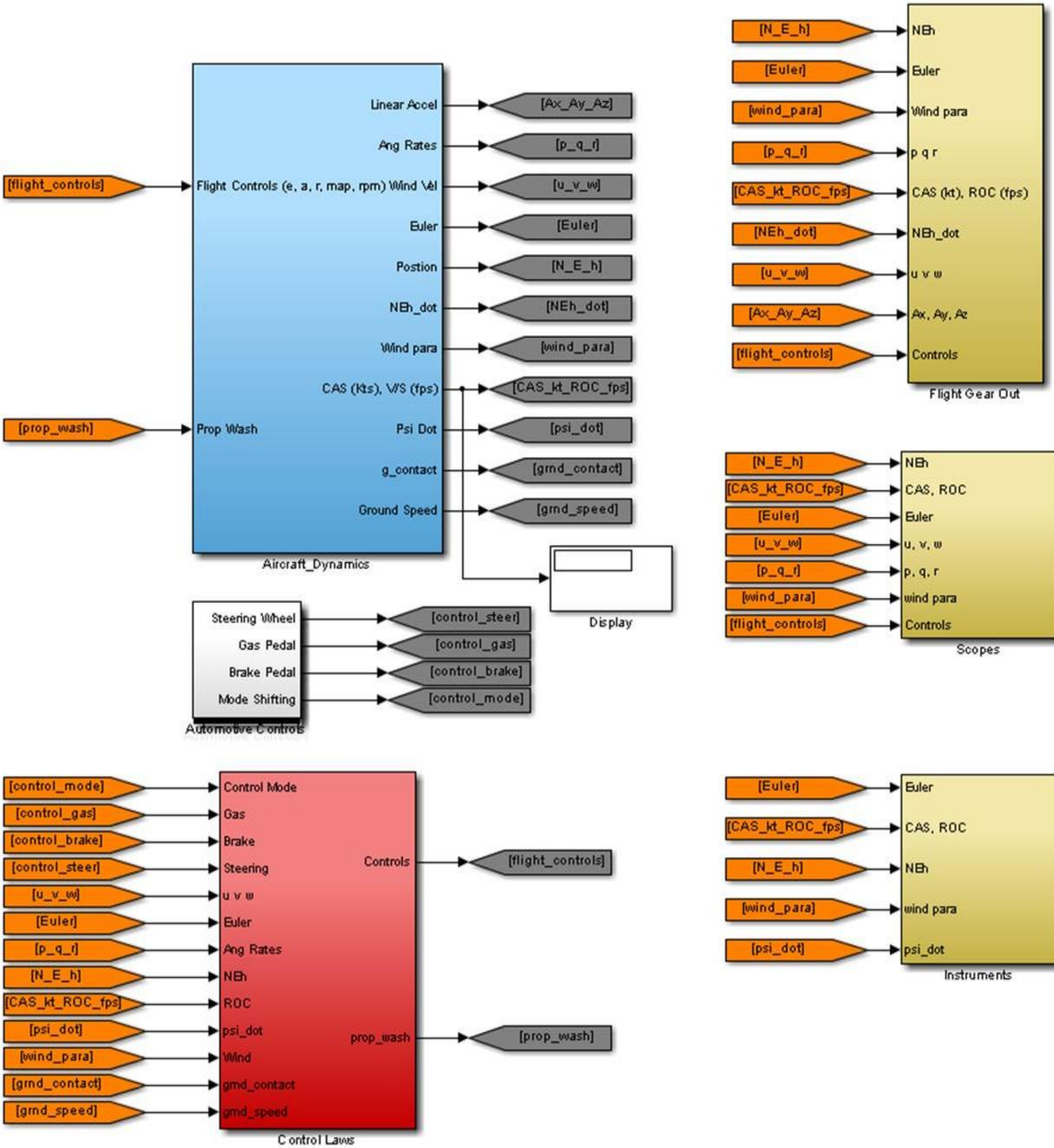


FIGURE 5: TOP LEVEL SIMULINK MODEL

2.3. Control Hardware

The control hardware consists of the Logitech® G27 racing setup. It includes a steering wheel, a six speed shifter, and gas/brake pedals. The steering wheel enables coordinated horizontal flight path control while the accelerator and brake pedals provide speed/rate-of-climb control depending on the flight mode selected. The shifter serves as the flight mode selector. There are seven flight modes which will be discussed in detail. The entire setup can be plugged into a computer using a USB cable and was relatively simple to integrate into Simulink using the joystick blocks from the aerospace block set. The control hardware can be seen in Figure 6. It should be noted that even though the hardware comes fully equipped with a clutch pedal, this pedal is not utilized for any purpose. Typical configuration is envisioned to be that of an automatic transmission automobile.

FIGURE 6: AUTOMOTIVE CONTROL HARDWARE

2.4. Out-the-Window View

For an out-the-window view, the simulation is interfaced with Flight Gear, an open source simulation. The default airport chosen is SFO, San Francisco International Airport, because the simulation developers are from that area and have developed the world model for that area with the highest fidelity. Flight Gear was adapted to interface with the simulation such that all of the vehicles states are fed in from the simulation via UDP at an update rate of 30 Hz, the approximate frequency of human perception. A simplified version of synthetic vision is also implemented through the visual interface. There are red follow-me boxes that have been inserted directly into the simulation environment for the test participants to follow so that pre-flight plans are virtually unnecessary (similar to driving a car; they simply have to follow the "road" laid out in front of them). Granted, this is not the full synthetic vision as developed by NASA, it is the most important aspect for the purpose of the development of the control laws which are meant to allow persons with little to no aviation knowledge or experience to fly an aircraft using automobile-like controls through the boxes with little training.

FIGURE 7: SIMULATION ROOM SETUP WITH FLIGHT GEAR PROJECTION

3. METHODOLOGY

3.1. Fusing Driving Skills with Control of an Aircraft

The motivation behind this thesis rests largely in the fact that just about every American adult knows how to drive a car and most of them drive often. By interfacing the operation of an aircraft with the driving skills required for an automobile, a pilot of this type will practice their skills on a day-to-day basis even if they don't have the opportunity to fly very often. This is also ideal for people who would only pilot an aircraft in this fashion once or twice a month. They won't need to fly often in order to keep the skills and mindset of a pilot. Their daily driving habits will be enough to keep them current.

Control of an automobile from a human factors standpoint has been thoroughly researched. Power management of an aircraft and automobile are so different that the control cannot possibly be modeled in the same fashion. The power management of an aircraft in the cruise phase of flight can, however be modeled similarly to that of a car on cruise control. The gas and brake pedal can act as the speed up and slow down mechanisms for the aircraft and the power will adjust accordingly, but during other phases of flight such as takeoff and landing, the power will be highly automated.

One of the more non-trivial tasks is use of the steering wheel in the car vs. use of the yolk in an aircraft. In an aircraft, the yolk controls two rotation axes of the aircraft, the roll and pitch axes. By rotating the yolk like turning the steering wheel in a car, the ailerons will be deflected causing an associated roll rate and will continue to roll until the yolk is centered. Once the yolk is centered, however the aircraft will remain at the bank angle it was at when the yolk was centered, and therefore the horizontal component of lift will cause the aircraft to turn until the yolk is rotated in the opposite direction and centered once again when the aircraft's wings are level at a bank angle of 0°. The yolk also has control of the pitch rate. If the yolk is pulled towards the pilot, the elevator is deflected up causing an associated nose up pitch rate. The aircraft will continue to pitch until the yolk is centered or until the aircraft's angle of attack becomes too large and the aircraft stalls. In order to pitch the aircraft down, the pilot has to push the yolk which would deflect the elevator down causing an associated nose down pitch rate.

An automobile's rate of turn is directly related to the amount of rotation of the steering wheel. The more the wheel is rotated, the higher the rate of turn will be. However, in this case once the steering wheel is centered, the automobile will no longer be turning. This is the effect desired when the steering wheel is rotated in the aircraft: the aircraft should develop a rate of turn (heading change) and that rate of turn should be zero when the steering wheel is centered. It should also be noted that in an automobile, the steering wheel can neither be pushed nor pulled because the automobile does not have six degrees of freedom like an aircraft does. An automobile has three degrees of freedom, but for the purpose of this control system, it is assumed that it has only two degrees of freedom since the normal operation of an automobile doesn't involve drifting or skidding on purpose. These two degrees of freedom would be forward translation and rotation about the vertical axis (turning). The aim of this thesis was to most closely model aircraft operation to these two degrees of freedom. An aircraft may translate in all three dimensions as well as rotate about all three axes, but this is the motivation behind the development of the flight modes.

The pilot had seven flight modes to choose from which will effectively only give them control of two degrees of freedom of the aircraft at a time. The aircraft degrees of freedom controlled by the pilot in this case will differ from the degrees of freedom controlled by a regular pilot in a typical fly-by-cable aircraft. In a typical fly-by-cable aircraft, the pilot has direct control over the throttle and rotations about all three axes by direct control of the elevator, ailerons, and rudder. For the pilot with a steering wheel, gas and brake pedals, and a shifter, he/she will only have control over the rate of turn of the nose of the aircraft by using the steering wheel and the translation of the aircraft either forward, up, or down depending on which flight mode is enabled. For example, when in climb mode, the gas pedal will make the aircraft translate upwards faster, whereas the brake pedal will make it translate upwards slower, but there will be no direct control over how fast the aircraft translates forward and vice versa in the cruise modes.

3.2. Flight Modes

Using the six speed shifter, there are seven flight modes available for the pilot to choose from depending on the flight phase. Shifting of the modes mainly changes what the gas and brake pedals do since the steering wheel is always used to change the horizontal path of the aircraft, similar to that of a car. These modes are in place to assist in changing or maintaining altitude primarily since direct control of the elevator has been taken away from the pilot. These modes also have different features when it comes to envelope protection depending on the portion of the flight profile, including different limitations to bank angle and active angle of attack monitoring. Figure 8 shows a standard six speed shifter which will be used to reference the "gears" in the following subsections.

FIGURE 8: STANDARD SIX SPEED SHIFTER

Figure 9 shows a very general diagram of how the Simulink model takes automotive control input from the user and converts that to aircraft control input for the simulation. Each flight mode has an associated set of control laws which contains the control logic required to fly the aircraft based on the pilot's automotive control inputs. All of these are working in parallel so that as soon as the flight mode is changed, the controls respond accordingly to transition smoothly to the next flight mode. A multiport switch is used to route the flight controls associated with the selected flight mode to the equations of motion.

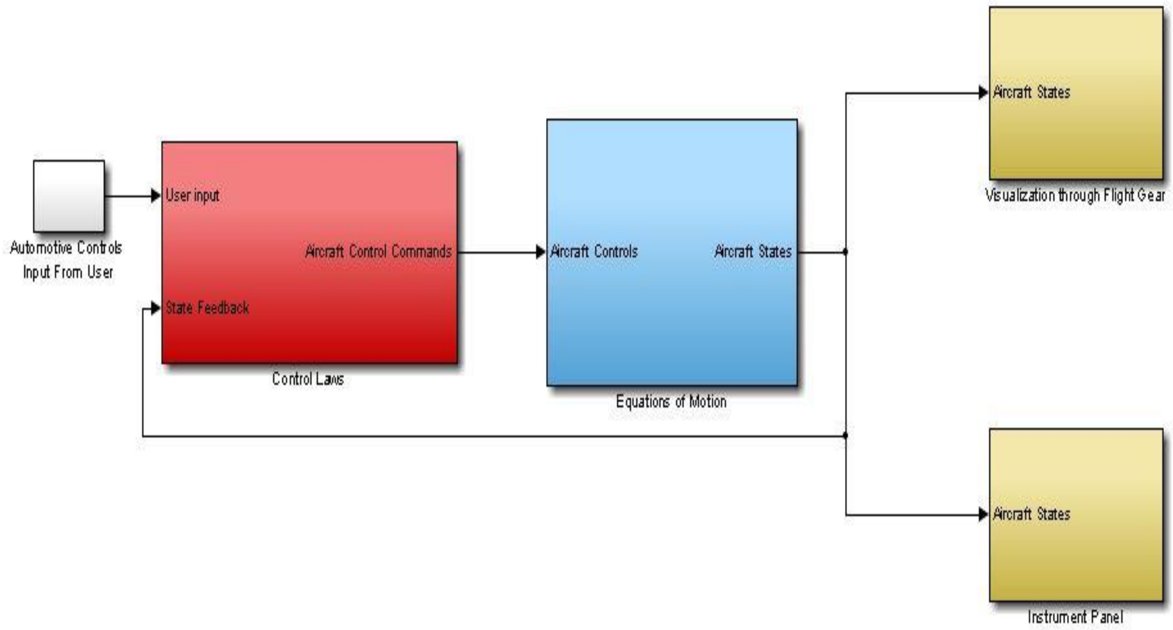


FIGURE 9: GENERAL BLOCK DIAGRAM

The red block entitled "control laws" contain all 7 sets of control laws corresponding to the different flight modes. The laws being used to feed the aircraft control commands in the equations of motion block depend on the position of the gear shifter. The automobile inputs from the user are from the steering wheel, gas and brake pedals, and the gear shifter. The two yellow blocks provide the visualization output for the user: the top one is for flight gear to provide the landscape and the bottom is for the instrument panel.

3.2.1. Taxi Mode

First, there is taxi mode. This mode would be engaged as soon as the aircraft is started with the shifter in the ‘reverse’ position for normal automobile operation. In taxi, the engine would remain at idle similar to an automobile. The gas and brake pedal would allow the pilot to increase throttle and apply the brakes, respectively, similar to that of an automobile. The steering wheel would have proportional control over the rudder which is used to turn while taxiing. In taxi mode, the aircraft would be operated almost exactly like driving an automatic transmission car. Once positioned on the runway ready for takeoff, it would be time to shift into takeoff mode. While shifting, when the knob is in between locked locations, the previous mode would still be engaged so the pilot would simply be expected to keep his/her foot on the brake until the aircraft has been shifted into takeoff mode.

3.2.2. Takeoff Mode

The takeoff mode is in the first gear position of the gear shifter. Once cleared for takeoff, the pilot would simply be required to push the gas pedal all the way for a full throttle takeoff. The pilot simply needs to remain on the runway and the aircraft will automatically pitch up to a 2° climb angle once ample airspeed is gained to prevent stalling at max gross takeoff weight. The brake pedal is used for aborted takeoffs; if there is something wrong and the pilot wishes to abort the takeoff, pushing the brake pedal will cut the engines power to idle, actuate spoilers and the aircraft’s wheel brakes. If the takeoff does not need to be aborted, when the aircraft is clearly above the runway and a positive rate of climb is observed, the pilot may shift into climb mode in order to have more control over the aircraft’s rate of climb.

Before shifting into climb mode, it is important to note that in takeoff mode, the steering wheel controls the aircraft in two distinct ways partitioned by whether or not the wheels are on the ground (wheels down or wheels up). When the wheels are down the steering wheel has proportional control over the rudder, similar to taxi mode in order to keep the aircraft centered on the runway during the takeoff roll and the ailerons will be automated to maintain a bank angle of 0° until the transition to wheels up occurs. Once the wheels are up, the steering wheel now commands a rate of turn in degrees per second with a limit on bank angle so that appropriate climb rates can be maintained. The logic for the pitch and roll rate commands can be seen in Figure 10.

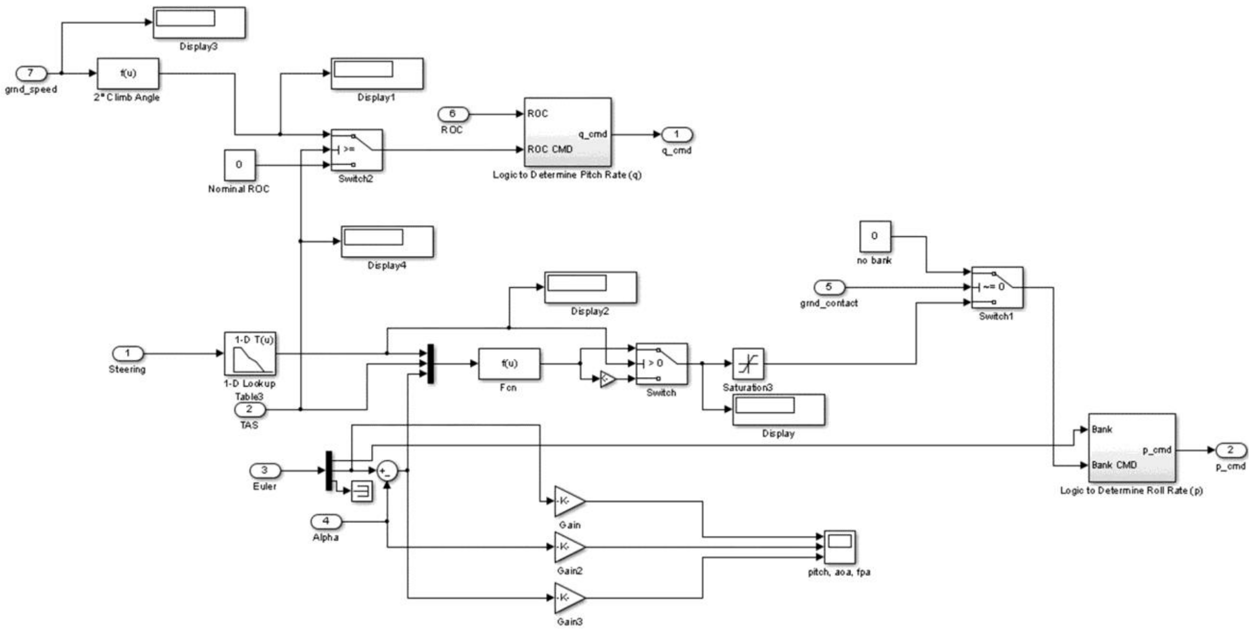


FIGURE 10: TAKEOFF MODE CONTROL LOGIC

3.2.3. <u>Climb Mode</u>

As stated before, once the pilot observes a positive climb rate and the takeoff has been completed, they will be able to shift into climb mode, which is the second gear position of the gear shifter. While in climb mode, a nominal climb of 300 feet per minute will be maintained if the pilot does not touch any of the controls. If the pilot chooses to climb at a slower rate, the brake may be used to decrease the rate of climb. When the brake is pushed down all the way, the aircraft will maintain altitude. If the pilot wishes to climb at a faster rate, the gas pedal may be used to increase the rate of climb to a maximum rate of 480 feet per minute. The steering wheel has control over the horizontal flight path. The rate of turn of the aircraft is determined by a lookup table corresponding to steering wheel deflection. For all modes, the rate of turn is proportional from 0 to 3 degrees per second corresponding to a steering wheel deflection of 0 to 90°. For steering wheel deflections beyond 90°, the rate of turn increases proportionally from 3 degrees per second to a maximum of 15 degrees per second. However, this maximum rate of turn is not always attainable during climb mode depending upon climb rate and airspeed because there is a limit on bank angle to ensure that appropriate climb rates can be maintained. The logic for the pitch and roll rate commands can be seen in Figure 11.

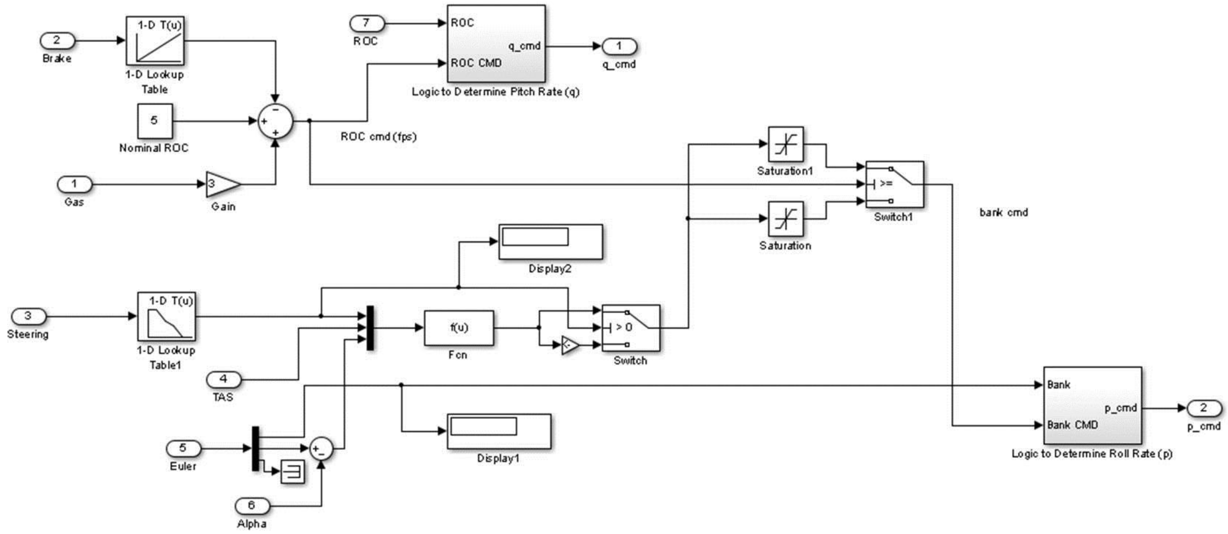


FIGURE 11: CLIMB MODE LOGIC

3.2.4. <u>Cruise Modes</u>

Once the desired altitude is reached, there are two cruise modes or settings that can be selected while in the cruise portion of the flight profile. First, it would be considered commonplace to hold down the brake pedal while in climb mode in order to maintain altitude before shifting to ensure a smooth transition. While in either cruise mode, the elevator is entirely automated to maintain the altitude that it was at when the cruise mode was selected. The two cruise settings are low and high speed cruise, with the gear shifter in the third or fourth gear positions respectively. These settings have the exact same control laws and operational attributes except for the power settings. The steering wheel has control over horizontal flight path with the same lookup table corresponding to rate of turn; for the cruise modes, a bank angle limitation of 45° will be implemented. The power setting for low speed cruise is nominally 65% and 75% for high speed cruise. While in the cruise modes, the gas and brake pedal work similarly to that of a car: when the gas pedal is pushed, it increases power, and when the brake pedal is pushed, it decreases power. In low speed cruise mode, the power is at 65% if no pedals are being pushed. If the brake pedal is pushed, it reduces the power proportionally down to a minimum of 45%. If the gas pedal is pushed, the power is increased proportionally to a max of 75%. If the pilot wishes to push the engine to even higher power output, they would shift into high speed cruise. In high speed cruise, the nominal power setting is 75% with no pedals being pushed. If the gas pedal is pushed, the power is increased proportionally to 100%. If the brake is pushed, the power is reduced proportionally to a minimum of 65%; if a lower power setting is desired, then the pilot would shift into low speed cruise. From cruise, the pilot may choose to shift into just about any other mode except for takeoff and taxi. They can choose to shift back into climb if a higher altitude is desired. They could also shift into descent to begin descending to a lower altitude to plan a landing or they can shift directly into landing mode if they so choose. The command logic for low speed cruise mode can be seen in Figure 12.

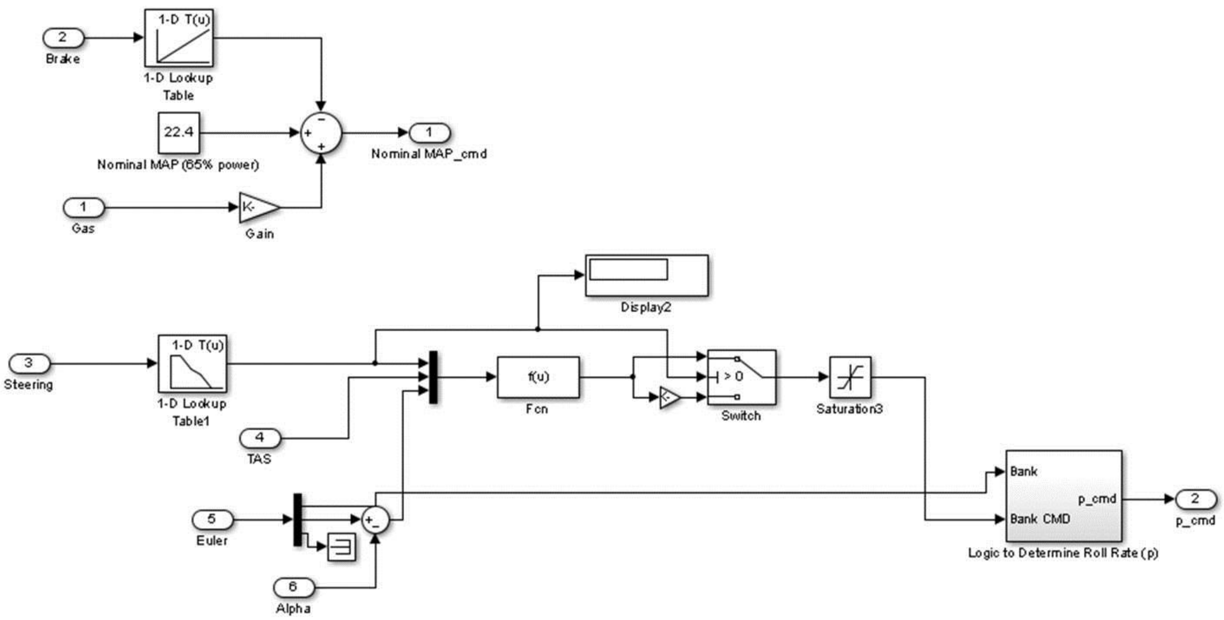


FIGURE 12: LOW SPEED CRUISE LOGIC

The logic for high speed cruise mode is exactly the same except for the MAP command logic differs in numbers only for different engine output as described above.

3.2.5. Descent Mode

Descent mode is very similar to climb mode; essentially it is complimentary. While in descent mode, which is fifth gear on the gear shifter, the aircraft is set to descend at a nominal rate of 420 feet per minute. If the pilot wishes to descend faster, the gas pedal will increase the rate of descent up to a maximum of 1020 feet per minute so long as maximum airspeeds are not surpassed. If the airspeed becomes too great, there are limitations to the descent rate coupled with pitch and power control laws to slow the aircraft down to more desirable airspeeds. If the pilot wishes to descend at slower rates, the brake pedal can be used to decrease the rate of descent. Fully pushing the brake pedal will cause the aircraft to maintain altitude. If the pilot were to go back to cruise mode, it would be considered commonplace to use the brake pedal to hold the desired altitude before shifting back into cruise mode for a smooth transition, similar to the transition from climb to cruise. However, if the pilot is descending to begin a landing approach, then it would be ideal to switch into landing mode once lined up with the runway. The command logic for descent mode can be seen in Figure 13.

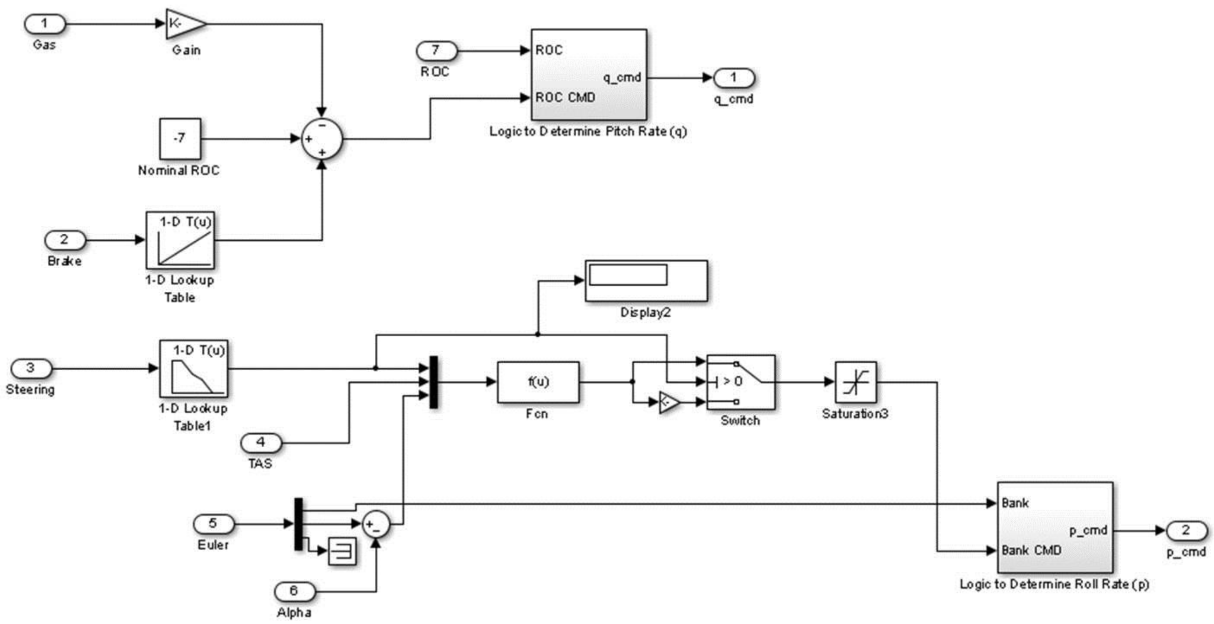


FIGURE 13: DESCENT MODE LOGIC

3.2.6. Landing Mode

In landing mode, the gas and brake pedal work similarly to descent, however rather than changing a commanded rate of descent, it changes the commanded glide slope. While in landing mode, the power is reduced to 40% so long as the glide slope can be maintained. Nominally, the glide slope is 3° as it is for a standard ILS approach. Also, with the help of the synthetic vision, the follow-me boxes will be set in a way that a 3° glide slope will keep the aircraft within the boxes so that the pilot will only need to worry about lining up with the runway laterally once inside the boxes rather than having to worry about glide slope. If the pilot is not at the proper glide slope already, the brake pedal will decrease the glide slope to a minimum of 0° maintaining altitude and the gas pedal will increase the glide slope to a maximum of 10°, however during an approach this can increase the airspeed quite a bit and may call for a go around which is simple with these controls; the pilot would need to hold the brake to maintain altitude, shift into climb, and when the brake is released, the aircraft will begin to climb on its own. Assuming that the pilot is within the follow-me boxes, the 3° glide slope is maintained in land mode and once the aircraft gets to a certain altitude, the flare maneuver is performed automatically so that the aircraft will land itself, which is a feat that has already been proven autonomously. While in landing mode there will be two sets of control laws for steering similar to takeoff mode: wheels up and wheels down. Wheels up condition is the same as always with some bank limitations and wheels down steering controls the rudder to keep the nose pointed down the runway. For landing mode, once the wheels are down, the brake's functionality changes as well. Once the wheels are all securely on the ground, the brake pedal will control the aircraft's brakes, return the engine to idle, and deploy aerodynamic speed brakes as well such as spoilers. The command logic for landing mode can be seen in Figure 14.

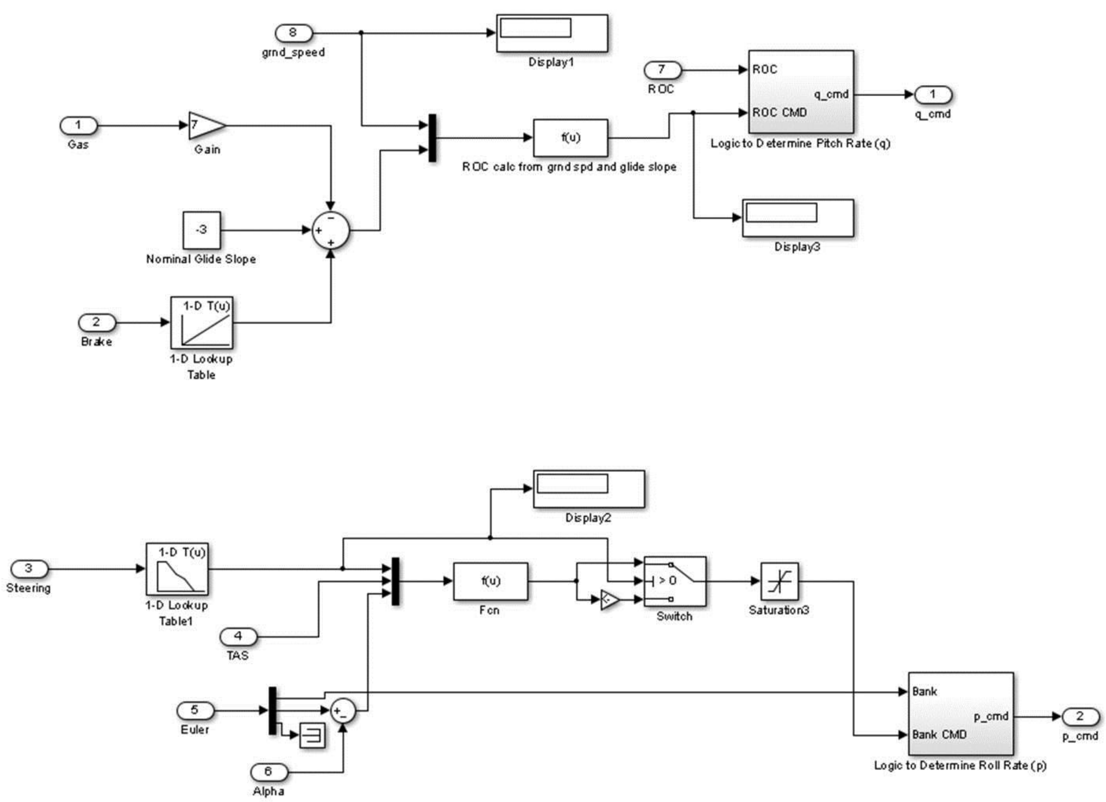


FIGURE 14: LANDING MODE LOGIC

3.2.7. Envelope Protection

There have been different types of envelope protection measures mentioned throughout the descriptions of the flight modes. Here is a brief overview of them. In takeoff mode, the bank angle is limited to ±20° regardless of altitude, rate of climb, or desired rate of turn. Once in climb mode, the bank angle is limited to ±20° during climbs at a rate greater than 300 feet per minute and is limited to ±30° for climbs less than or equal to 300 feet per minute. In cruise mode, the bank angle is limited to ±45° to prevent wing tip stalls and unwanted spins especially since the pilot does not have direct control of the rudder. It is assumed that any aircraft using these control laws will have a start of the art data acquisition system capable of detecting wind angles such as angle of attack and angle of sideslip, AOA and AOS respectively. Throughout all modes of flight, AOA will be monitored to ensure that the critical AOA is never reached. In the event that the critical AOA is being approached, the flight computer will take control of certain control parameters in order to reduce the AOA while still adhering to as many pilot commands as possible. Audible and visual stall warnings would be used to alert the pilot to operate the aircraft at a more stable condition. The rudder will be completely automated for envelope protection throughout the entire flight as well. Depending on which flight mode the pilot has selected determines how the rudder is operated. While in takeoff and landing mode, the rudder will be automated to maintain the aircraft's GPS ground track with no steering wheel deflection. If the steering wheel is deflected, the rudder will respond accordingly to change the ground track. For landing, just before the flare maneuver, the rudder will be automated to align the nose of the aircraft with the GPS ground track. In all other modes of flight (climb, cruise, descent), the rudder is used purely for coordinated turns. There will be a simple PI controller feeding back AOS to the rudder input. This will always use the rudder to drive AOS to 0° for coordinated turns during flight outside of takeoff and landing.

Accidental shift-out protection is provided by the shifter. If the pilot accidentally knocks the shifter out of its current mode into neutral, the previous mode will remain engaged until a new mode is selected. Some of the reasoning behind these modes and the "shift-out protection" were driven by the available hardware. Ideally, the shifting would be similar to a sequential shifter in an automatic transmission vehicle. This would change the standard operating procedures only, not the actual structure of the flight modes.

3.3. Control Law Development

Once the flight modes were developed and it was determined how the automotive controls will control the aircraft, the development of the control laws became somewhat simpler. For wheels down modes such as taxi, takeoff, and landing, the steering wheel has direct control over the rudder for directional control on the ground. For all other flight modes, the steering wheel commands a rate of turn which is somewhat different from how a normal aircraft operates. First, it needs to be understood that an aircraft turns by rolling. When the aircraft is rolled, the horizontal component of lift will turn the aircraft. However, in a car the driver will keep the wheel turned in order to keep the car turning, while in an aircraft, the pilot would center the yolk to keep the aircraft banked. This is where the fusion of command and control comes into play. To turn the steering wheel is to command a rate of turn or a rate of heading change. The control law will then use the ailerons to affect a roll rate until one of two conditions is met. The first condition being that the commanded rate of turn is met and the aircraft should maintain a roll rate of zero to maintain the rate of turn. The second condition would be that the maximum allowable bank angle is met; this would be put into place for envelope protection purposes. The maximum allowable bank angle depends on the portion of flight as well as other limiting factors such as rate of climb.

The bank angle required in order to maintain a commanded rate of turn can be calculated using an equation from [12] assuming that the flight path angle, γ, can be measured. As stated previously, a data acquisition system capable of measuring θ and α will be used so γ can be calculated.

$$\Phi = cos^{-1} \frac{1}{\sqrt{\dot{\Psi}^2 * \frac{V_{TAS}^2}{32.2^2} + \cos(\gamma)^2}}$$

In the equation above, the bank angle, Φ, can be calculated provided a commanded rate of turn, $\dot{\Psi}$, the true airspeed in ft/s, and the flight path angle.

The longitudinal control laws have been developed very similarly to the lateral ones. In climb mode, the pilot has the ability to increase the rate of climb by stepping on the gas pedal, and decreasing it by stepping on the brake pedal. In order for the aircraft to increase its rate of climb at a given power setting, the elevator will be used to affect a nose up pitch rate until one of two conditions is met. First condition being that the commanded rate of climb is met, in which case the commanded pitch rate becomes zero to maintain the rate of climb. The second condition would be that the aircraft is approaching the critical angle of attack or is approaching stall. If this were the case, the stall horns would go off, and the pitch rate would drop to zero to maintain the highest possible rate of climb without going beyond a pre-determined angle of attack to prevent stalling. The brake pedal would work conversely. The elevator would be used to affect a nose down pitching moment until the commanded rate of climb is met.

In descent mode, the control laws would work exactly as described above, but exceeding the “never exceed” velocity, V_{NE}, is now prevented. While in descent mode, if the pilot chooses to descend at a higher rate of descent, he/she would push the gas pedal. This would cause the elevator to affect a nose down pitch rate until one of two conditions is met. The first condition, of course, being that the commanded rate of descent has been met, in which case a pitch rate of zero will be commanded in order to maintain this rate of descent. The second condition being that V_{NE} is being approached and the aircraft must be slowed down in order to be operated safely. If this condition occurs, there will be a nose up pitch rate commanded until a suitable deceleration is attained and a safe operating velocity is reached in which case full, normal control would be returned to the pilot.

In takeoff and landing mode for the wheels up portion of flight, the gas and brake pedals work much in the same way described above for the climb and descent modes. However, in these modes, the gas and brake pedals command a climb or glide angle. Of course, the ground speed and true airspeed is taken into account in order to maintain a given angle of ascent or descent. In these modes with the wheels down and in taxi mode, the gas and brake pedal work much like they do in a car. The gas increases power output of the engine returning to idle if not pressed, and the brake pedal will apply the brakes on the wheels.

As can be seen in figures 10 through 14, the rate of turn or rate of climb/descent commands are calculated from the control inputs. In climb mode, for example, if the pilot wishes to begin climbing at a higher rate, he/she would push the gas pedal. This would increase the rate of climb commanded and then there's some logic to determine the appropriate pitch rate based on the current rate of climb and the commanded rate of climb to drive the error between the two to as close to zero as possible. This logic can be seen in Figure 15.

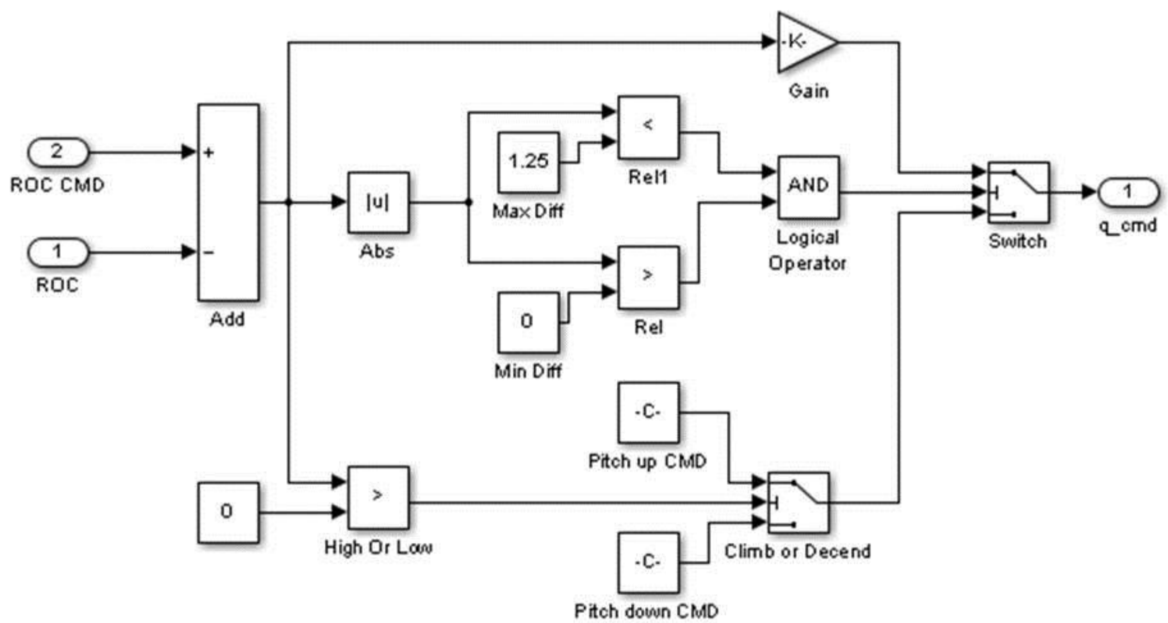


FIGURE 15: LOGIC TO DETERMINE PITCH RATE

Similarly, the roll rate is determined with some logic statements pertaining to the difference in the current bank angle and the bank angle required to maintain the commanded rate of turn as calculated previously. This logic can be seen in Figure 16. For both the logic to determine the roll and pitch rates there is a logical AND statement which determines when the error between commanded and current state is close enough to begin tapering off the commanded roll or pitch rate. This will allow for smooth transitions between turning/climbing while minimizing oscillatory motions providing a comfortable ride for the pilot.

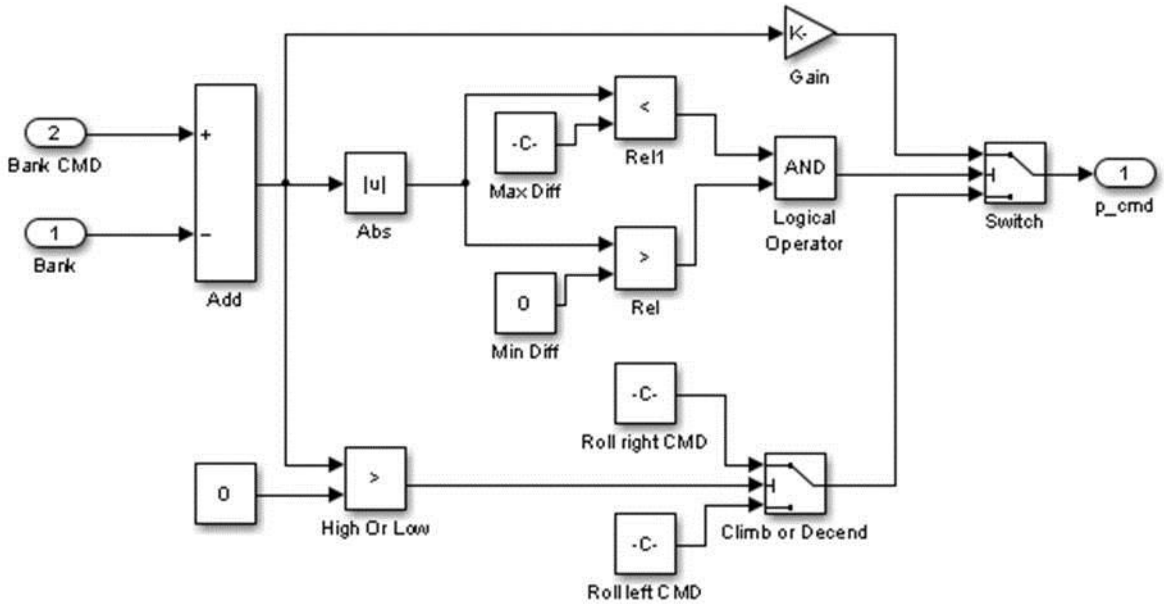


FIGURE 16: LOGIC TO DETERMINE ROLL RATE

Due to time constraints and current state-of-the-art autonomous systems, for the purpose of the development of this system, the auto-flaring capability during landing mode was not developed for the simulation. Recently, the Navy has demonstrated that it is possible to land a UAV autonomously on an aircraft carrier, so it is safe to assume that a landing algorithm may be developed for landing on a stationary runway. Also, the purpose of this thesis is not to demonstrate that control laws may be developed for the autonomous landing of an aircraft, it is to demonstrate the capabilities of the new control laws to safely and effectively fly an aircraft using automotive control hardware.

The control methodology primarily used is Linear Quadratic Regulation (LQR) with full state feedback. This is a relatively modern control technique used in industry that is more robust than classical PID controllers which require multiple feedback loops for stability augmentation and navigation. LQR requires only one feedback loop to regulate certain states for stability augmentation and others to a commanded state for navigation purposes.

The state-feedback law of $u = -Kx$ minimizes the quadratic cost function provided below.

$$J(u) = \int_{0}^{\infty} (x^T Q x + u^T R u + 2x^T N u) dt$$

This cost function is subject to the system dynamics provided by the Navion model. The matrix K is determined by solving the matrix Ricatti equation for S and substituting into the subsequent equation. The matrix Ricatti equation is as follows.

$$A^T S + SA - (SB + N)R^{-1}(B^T S + N^T) + Q = 0$$

Once solved for S, the following equation provides the matrix K which is multiplied by the fed back states, x, to obtain the proper control deflections, u, which will regulate the desired states.

$$K = R^{-1}(B^T S + N^T)$$

The determination of the Q and R matrices is an iterative process where the diagonal of Q is directly related to the states being regulated and the diagonal of R is related to the controls used. In this method, all of the relevant states are fed back and multiplied by a matrix of gains, K, to produce the proper control deflections in order to regulate these states. Each flight mode has its own set of control laws with a respective LQR feedback loop for different performance characteristics depending on the flight mode chosen.

Depending on the flight mode and the phase of flight, it is sometimes difficult to regulate all of the states pertaining to the aircraft's attitude using all of the flight controls. The climb mode, for example, has required two LQR feedback loops to maximize the maneuverability and stability of the aircraft during steep climbs while turning. Figure 17 shows the block with the command logic which feeds into the blocks containing the fed back states and the LQR gain matrices.

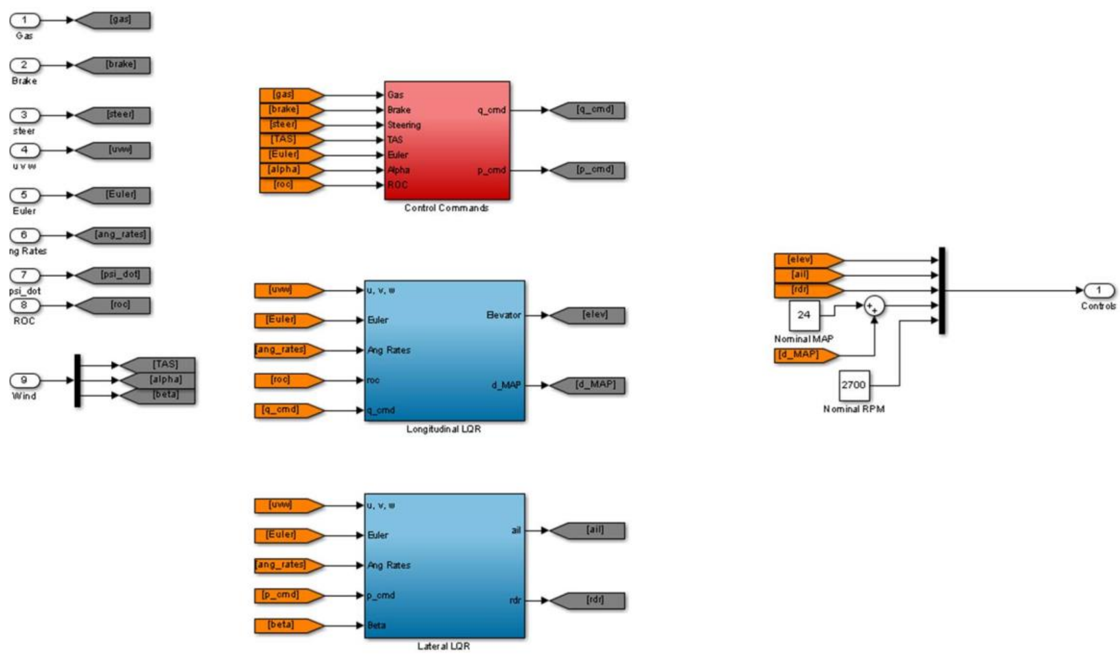


FIGURE 17: CLIMB MODE CONTROL COMMANDS AND LQR BLOCKS

Once the command logic determines the value of the pitch or roll rate that needs to be affected, these values are fed into the LQR blocks along with the states that are fed back from the plant. The following two figures will show what the longitudinal and lateral LQR blocks look like.

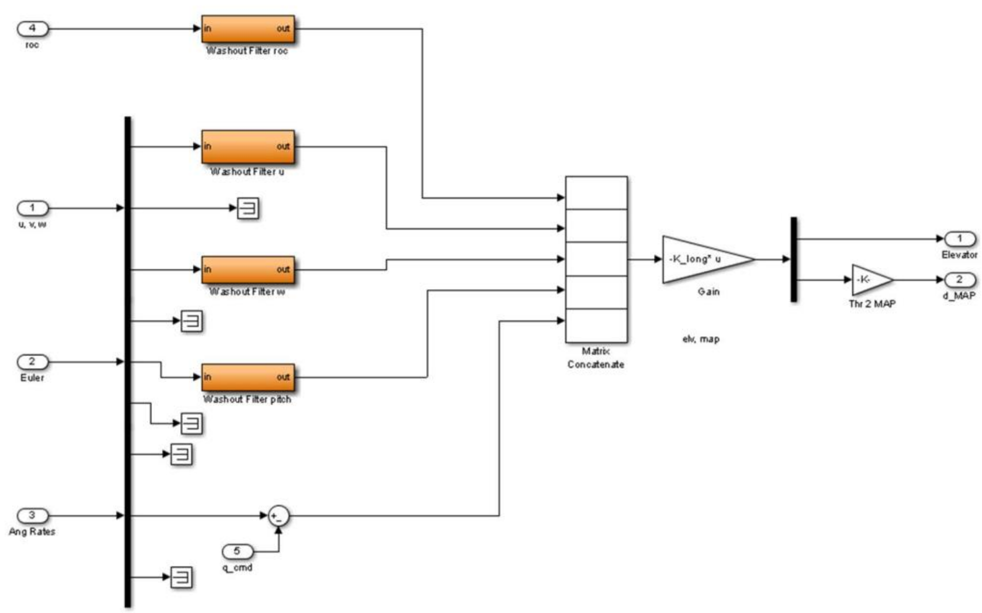


FIGURE 18: CLIMB MODE LONGITUDINAL LQR

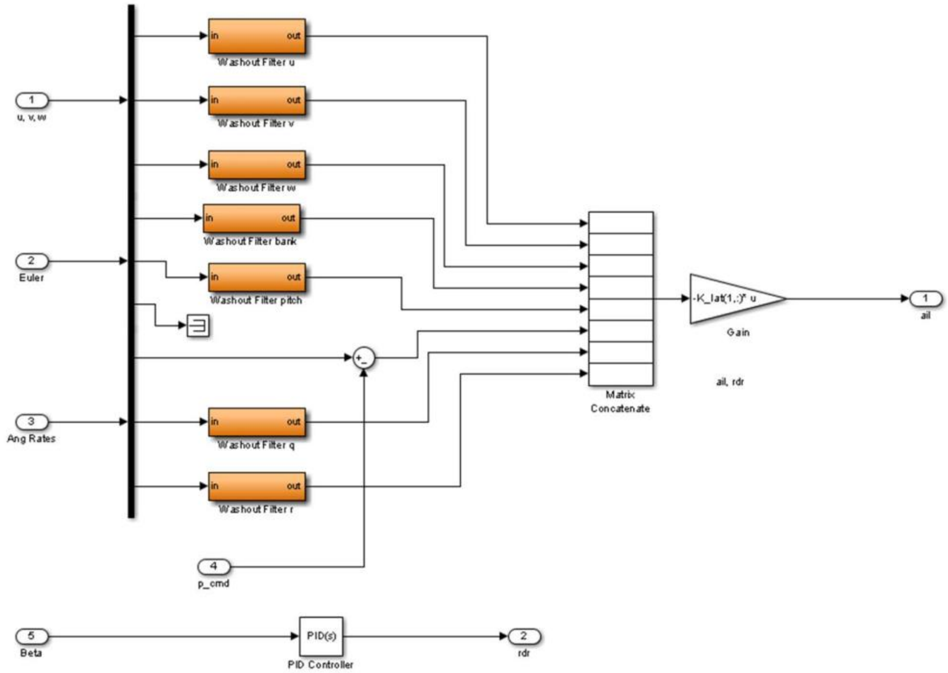


FIGURE 19: CLIMB MODE LATERAL LQR

As can be seen in the above figures, the regulated states are fed through washout filters to minimize the change in these states while the commanded states are subtracted from the corresponding fed back states in order to minimize the error between these two. Notice in the lateral LQR block, there is a PID controller feeding back AOS directly to the rudder in order to always drive it to 0°. It is, however, only a PI controller because the damping gain is 0.

3.4. Human Subject Testing

There were 20 participants split into three categories. There were 9 non-pilots ranging in age from 15 to 69. Two of the non-pilots were male, the rest female. These participants had no flight hours and little to no knowledge of aircraft whatsoever. There were 5 student pilots ranging in age from 18 to 36. Three of them were male, two female. These participants included students with zero flight hours who were just beginning to take classes on aviation as well as students still new to aviation with up to 50 flight hours. There were 6 experienced pilots ranging in age from 21 to 59. Four of them were male, two female. The experienced pilots ranged in flight time from 400 to 5000 hours. Most of them were still students nearing the rating of commercial pilot. Some of them were career pilots.

The human factors experiment was setup in a way that all human subjects would receive the same briefing on the control system and then they would have the opportunity to fly the same three scenarios. Each subject would only spend about an hour and a half total between the briefing and the flight scenarios at which time they would fill out a survey that had a number of quantitative and qualitative questions for them to answer in order to aid the development of the control system. An adapted version of the system usability scale was used to provide a score out of 100 for a good quantitative measure of the usefulness of the system. The Cooper Harper rating scale was also used for the subjects to rate the handling characteristics of the aircraft from 1 to 10. In this rating scale, a lower number means the aircraft handles better with 10 being the aircraft cannot be handled at all. A flow chart of how to rate the handling qualities is provided in the survey that the participants actually took in APPENDIX B – Usability Survey. If the aircraft is able to be controlled and flown in a manner that you're able to get from point A to point B safely, then a Cooper Harper rating ≤ 3 is typical.

Before the human subjects were brought in for the testing, the highway in the sky follow-me boxes were generated by flying the three scenarios ahead of time. The first scenario was a typical pattern flight where the aircraft started on the runway at San Francisco International Airport, SFO. The subject was expected to be able to takeoff, climb to a nominal altitude of 1000 feet, circle around the airport and land on the same runway. The second scenario was a short flight to San Carlos Airfield, just minutes away from SFO. For this scenario, the subject would start on the runway, takeoff, climb to cruising altitude, cruise for a few minutes before beginning the descent to San Carlos where they would land. The third scenario was a longer flight that typically took about 20-25 minutes from SFO to Oakland International Airport just across the San Francisco Bay. The subject performed the same flight maneuvers for this scenario as in the second except that about halfway through the cruise portion of the flight profile, the aircraft was required to climb to a new cruising altitude.

For all three scenarios, there was a static highway in the sky composed of red follow-me boxes. It was static in the sense that the follow-me boxes would not move or update if the pilot were to veer outside of the highway. If that were to happen, then the pilot would have to maneuver the aircraft back into the boxes in order to continue along the outlined flight path. This served two purposes: one, an intelligent path planning algorithm would not need to be developed and two, the aircraft's flight path can be used as a performance measure to determine the level of difficulty for pilots to control the aircraft by following the prescribed flight path.

Control input is another performance measure that was recorded during the experiment in order to determine pilot workload. It is desirable that the pilot remains engaged enough to not become complacent, but also to not have to do so much that it becomes difficult and confusing to operate the aircraft. The control inputs that were recorded are steering wheel deflection, gas and brake pedal deflection, and flight mode (i.e. shifter position). These will be used to aid in the illustration of pilot workload required to fly an aircraft with this control system.

4. RESULTS

The following subsections outline the results of the human factors testing performed according to the demographics recorded. A sample from each group of subjects is provided. For each subject, there is a brief introduction of their background along with some demographic information. A score out of 100 will be provided by the modified system usability scale. The Cooper-Harper rating will also be provided along with some qualitative feedback.

A good measure of how well the subject actually handled the aircraft will be the plots of the outlaid course and their actual course flown. In these figures, the course of the follow-me boxes will be provided in blue and the course flown by the subjects will be provided in red. These will be provided in two and three dimensions. It is important to keep in mind that the follow-me boxes were about 50 feet square so an altitude of about ±25 feet away from the prescribed course is still considered to be acceptable. There will also be time histories of the steering wheel, gas pedal, brake pedal, and shifter inputs to provide an idea of pilot workload required. The gas and brake pedal inputs have both been normalized from 0 (not pressed) to 1 (pressed down all the way). The steering wheel deflection will be provided in degrees. The full travel of the steering wheel is ±450° with positive deflection being to the right. The shifter position is provided as a discrete integer referring to which flight mode the pilot has selected from 1 to 7. For this study, it is only going to be shown from 1 to 6 because the simulations always began with the aircraft already on the runway so flight mode 7, taxi mode, was never used.

Each subject was given fifteen minutes to read through a power point presentation outlining the control system and how to fly the aircraft. They were all allowed to go through this presentation at their own leisure and to use up as much or as little time necessary not exceeding the fifteen minutes. None of the subjects used the full allotted fifteen minutes to study the control system. The power point introduction used can be seen in APPENDIX C – Pre-Flight Training Presentation for HF Testing

4.1. Non-pilots (NP)

There were 9 non-pilots. The non-pilots category represents a wide variety of people from different backgrounds with little to no aviation knowledge whatsoever including a fifteen year old who didn't even have a driver's license at the time of the test. It is important to note that the majority of this category is over the age of 40 with no aviation knowledge whatsoever; this would be the targeted demographic for the use of this technology in the national transportation system. A sample of the results from a non-pilot subject is provided below.

This non-pilot participant was a 22 year old female. The participant had no previous flight experience including with flight simulators or even video games. The participant was not familiar with aircraft controls, but did have a driver's license for about 5 years and drove a car with an automatic transition. With our modified form of the system usability scale, this participant scored the system as 75 out of 100 and gave the handling qualities an 8 on the Cooper-Harper scale, but it's possible that the scale was misunderstood.

This participant rated the overall experience at 9.5 out of 10 stating that it was "fun and simple, at first it's kind of hard to get used to it…with some practice I could actually fly a plane like this." A little more training and tips may have been useful for this candidate, but the scenarios were completed with little trouble. The following subsections will outline the scenarios.

Pattern Flight

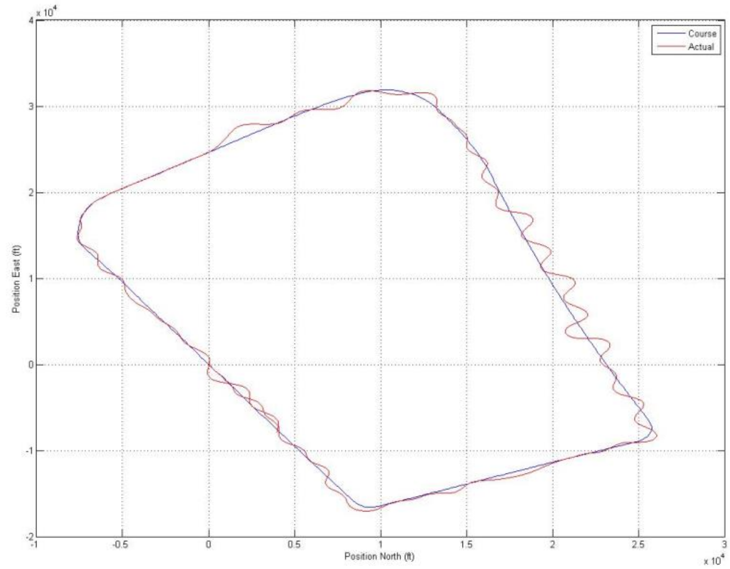


FIGURE 20: NP1 - PATTERN FLIGHT PATH IN TWO DIMENSIONS

It is clear that the participant didn’t have very good control over the horizontal flight path of the aircraft. You’ll also be able to see in the figure displaying the steering input that there was a very high pilot workload required to fly the path shown in red.

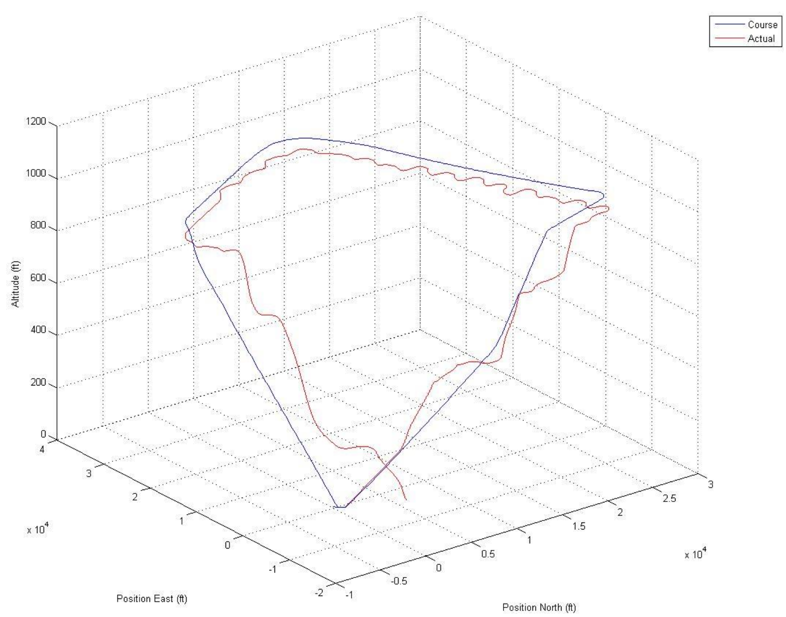


FIGURE 21: NP1 - PATTERN FLIGHT PATH IN THREE DIMENSIONS

In the figure above, it can be shown that the participant controlled altitude fairly well, but was clearly unable to control the horizontal flight path and stay within the follow-me boxes. Below, in Figure 22, the steering input saturated many times throughout the entire flight. This is because the participant was turning the steering wheel all the way to one side and then all the way to the other. It was evident that the participant wasn't familiar with flight dynamics or trajectory tracking in an aircraft, but throughout the scenarios, this hurdle was overcome and the workload decreased accordingly.

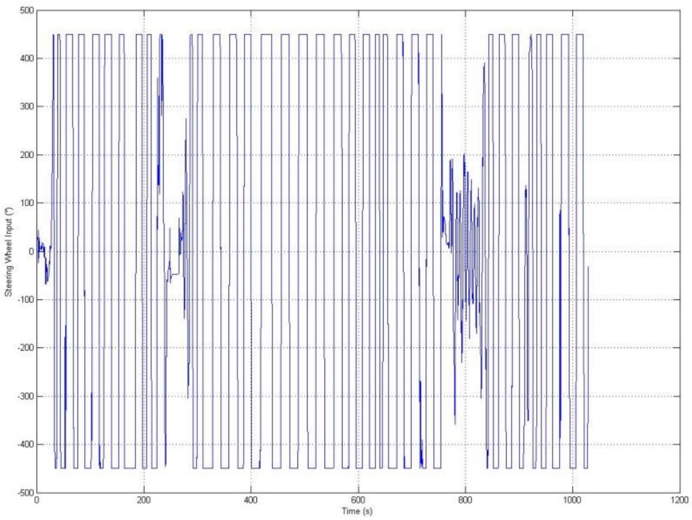


FIGURE 22: NP1 - STEERING WHEEL INPUT

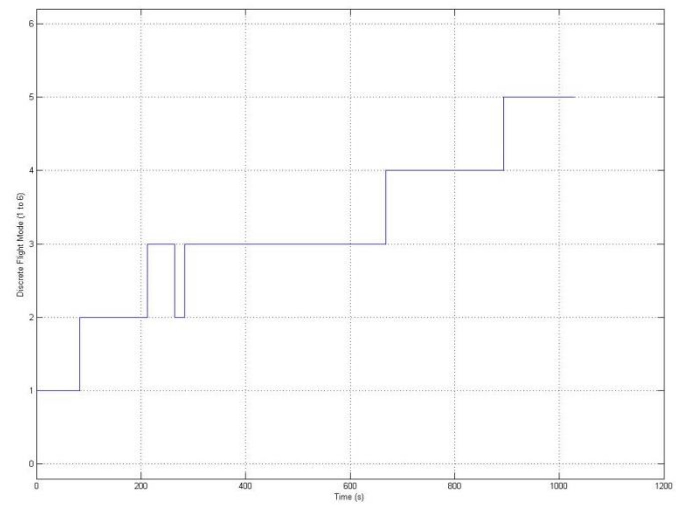


FIGURE 23: NP1 - SHIFTER INPUT

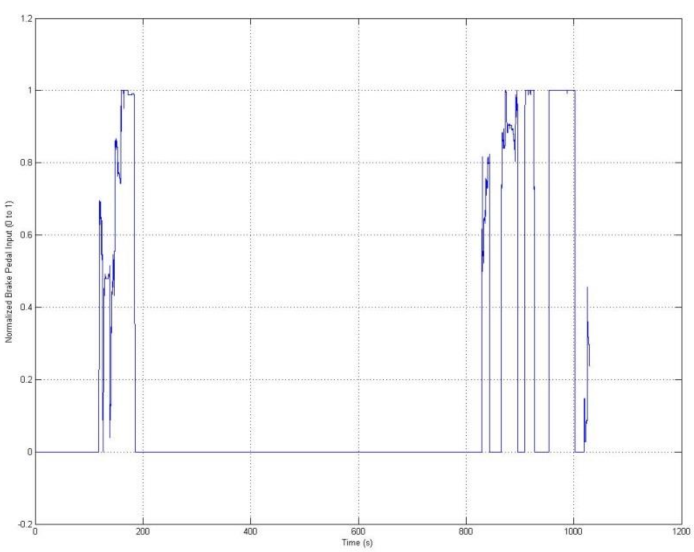


FIGURE 24: NP1 - BRAKE PEDAL INPUT

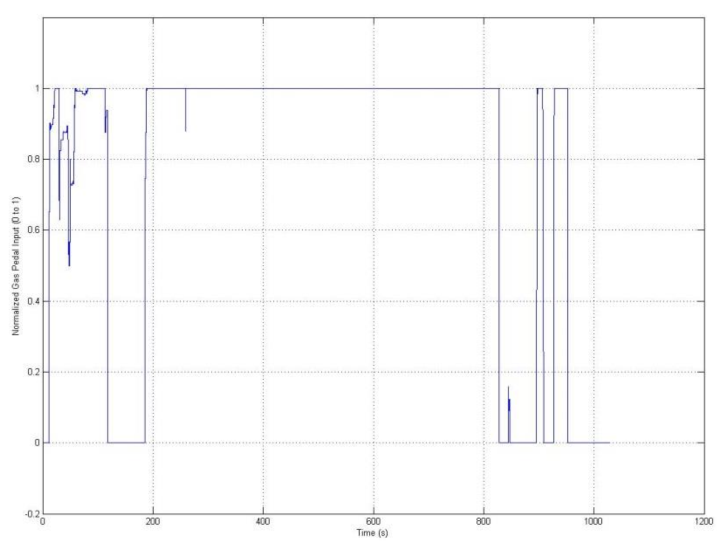


FIGURE 25: NP1 - GAS PEDAL INPUT

San Carlos Flight

It is shown in the following figures that the participant's flight skills increased during the second flight. There was far better control over horizontal flight path, but slightly more trouble controlling altitude this time around. It will be shown that the workload was still considerable

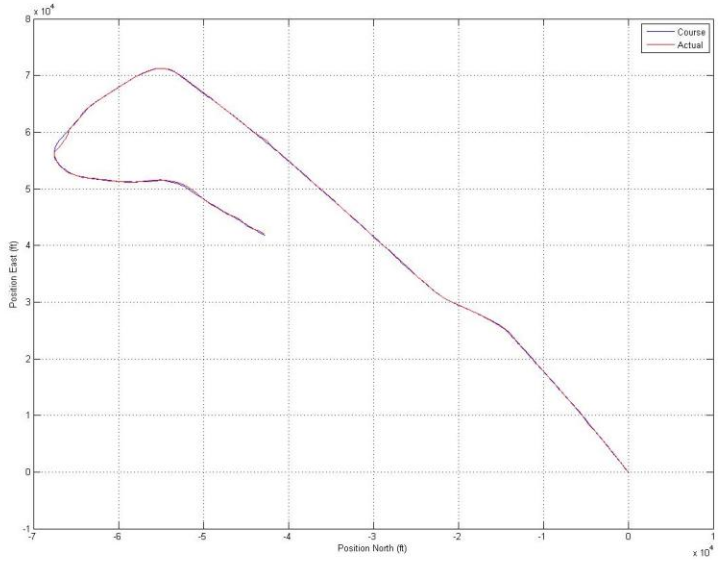


FIGURE 26: NP1 - SAN CARLOS FLIGHT PATH IN TWO DIMENSIONS

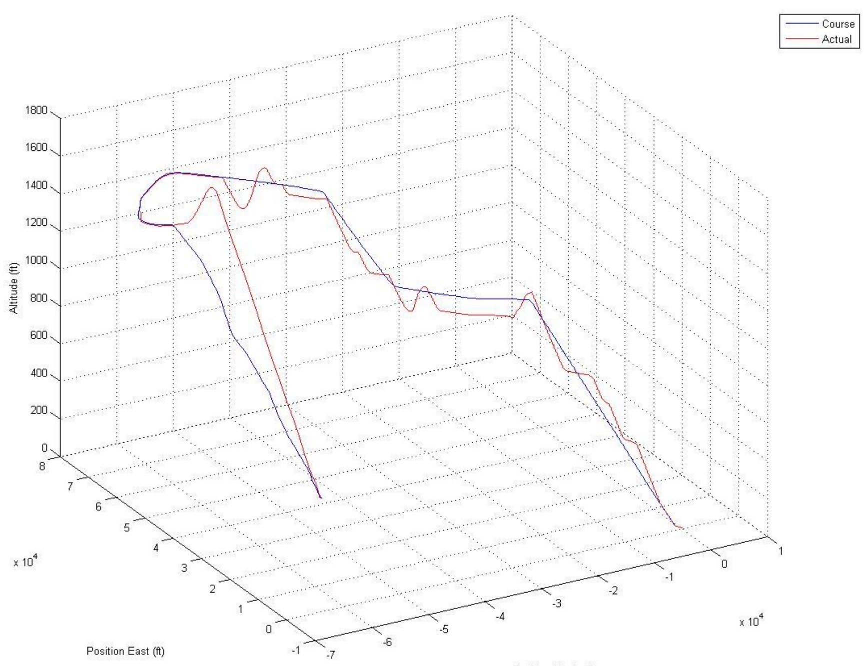


FIGURE 27: NP1 - SAN CARLOS FLIGHT IN THREE DIMENSIONS

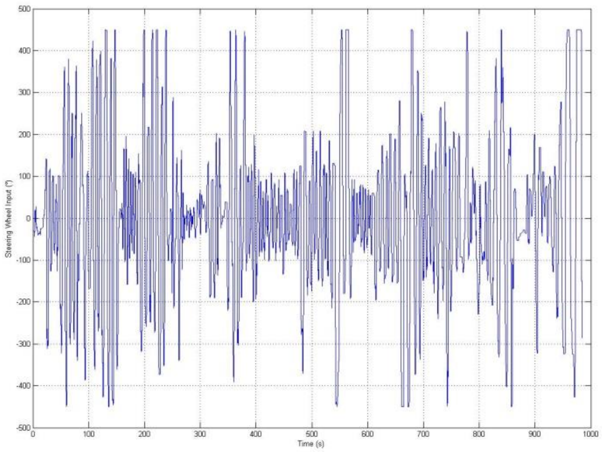


FIGURE 28: NP1 - STEERING WHEEL INPUT

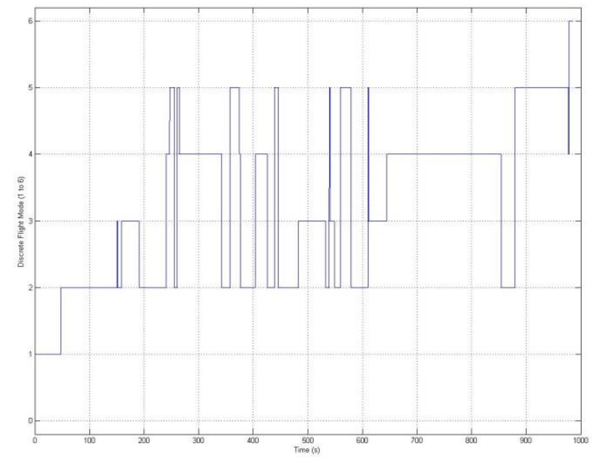


FIGURE 29: NP1 - SHIFTER INPUT

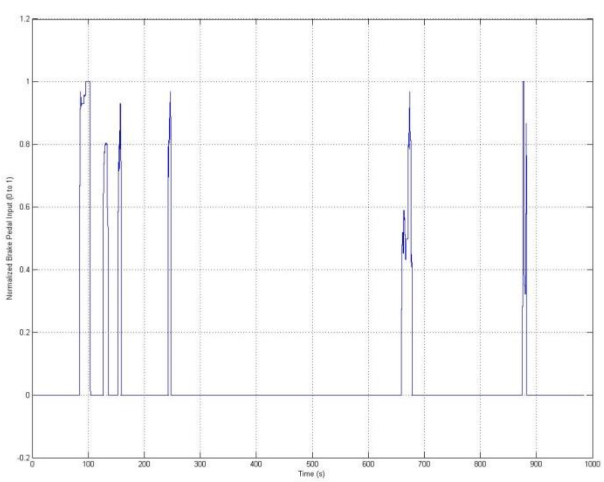


FIGURE 30: NP1 - BRAKE PEDAL INPUT

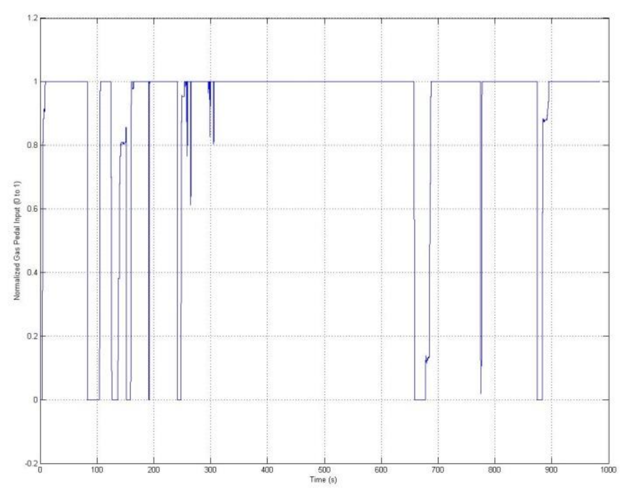


FIGURE 31: NP1 - GAS PEDAL INPUT

Oakland Flight

During the third and final scenario flight from SFO to Oakland, the participant demonstrated far better control over the aircraft. The prescribed flight path was tracked with minimal workload.

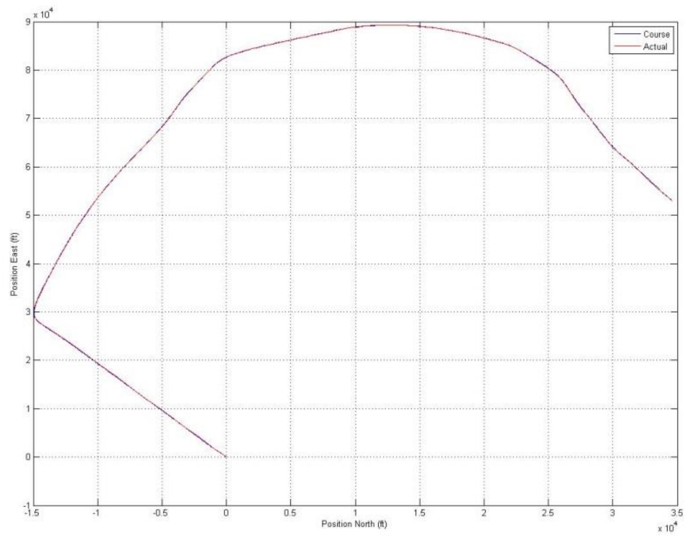


FIGURE 32: NP1 - OAKLAND FLIGHT PATH IN TWO DIMENSIONS

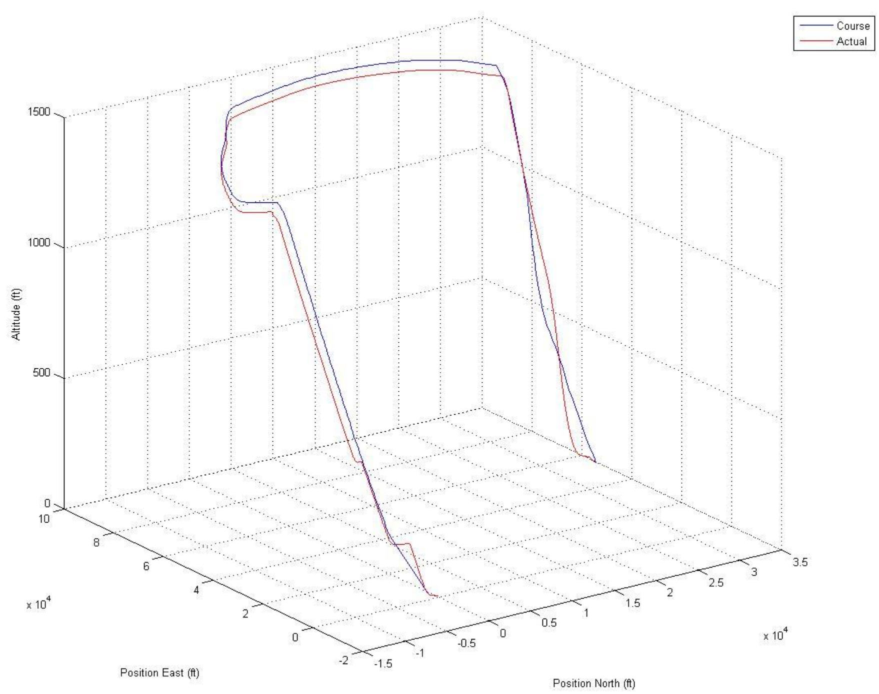


FIGURE 33: NP1 - OAKLAND FLIGHT PATH IN THREE DIMENSIONS

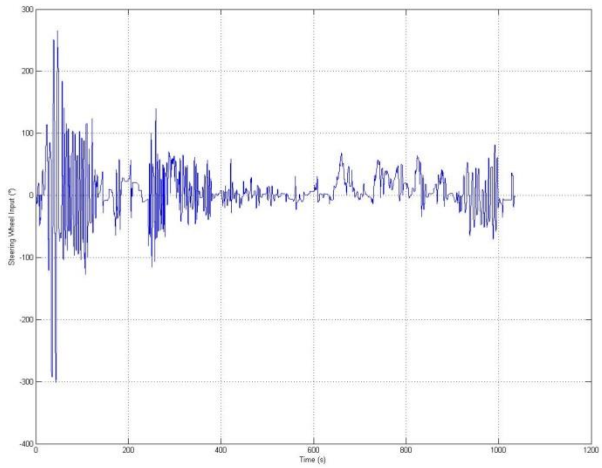


FIGURE 35: NP1 - STEERING WHEEL INPUT

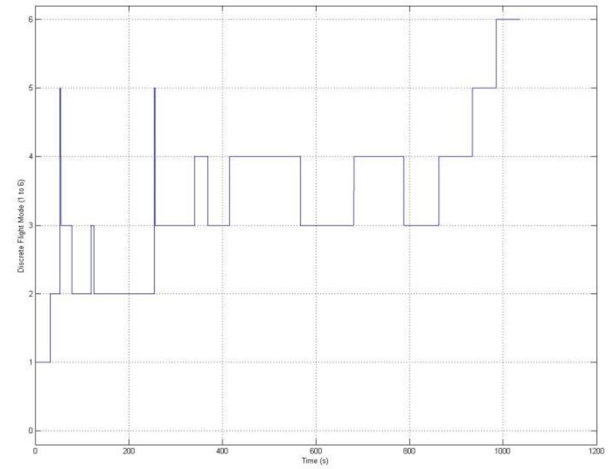


FIGURE 34: NP1 - SHIFTER INPUT

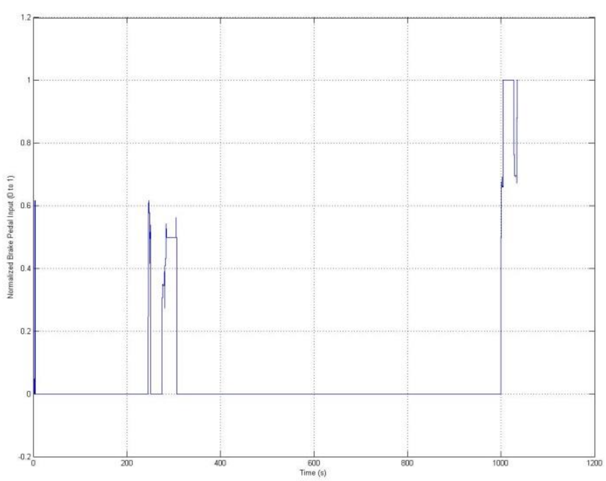


FIGURE 36: NP1 - BRAKE PEDAL INPUT

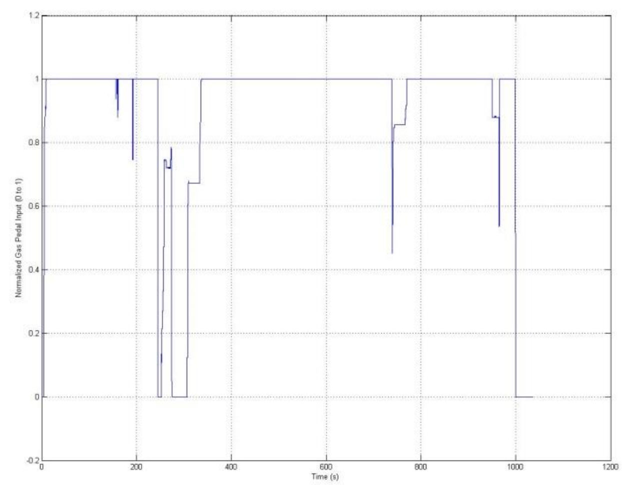


FIGURE 37: NP1 - GAS PEDAL INPUT

As you can see in the four figures above and the other control related figures from the previous two flights, the participant got used to the controls over time and the pilot workload decreased as skill increased. It is noticeable from the first flight that there was some trouble with horizontal flight path and staying inside the follow-me boxes; this is evident from the course shown in Figure 20: NP1 - Pattern Flight Path in Two Dimensions. By the second flight, the participant seemed to have better control over the aircraft, but was then having some issues with altitude control. The prescribed trajectory was tracked well, but there was still a relatively large workload as evidenced from the steering wheel input from the San Carlos flight. By the third flight it is clear from the two course figures shown that the participant demonstrated greater control over the aircraft with a much lower pilot workload. This demonstrates how quickly and easily someone with no flight experience whatsoever will be able to pick up on this control methodology quickly simply by using their knowledge and learned driving habits.

4.2. Novice Student Pilots (SP)

There were 5 student pilots. The student pilots category represents student pilots at ERAU with anywhere from zero to 100 flight hours. The majority is currently seeking or only has a rating of private pilot. A sample of the results from a student pilot is provided below.

This student pilot subject was a 22 year old female. At the time, this participant had 22 flight hours and felt comfortable knowing a majority of the typical flight controls. This participant did not have a driver's license, however, and therefore is not extremely familiar with typical driving habits. A score of 80 out of 100 was given with the modified SUS and a Cooper-Harper rating of 2 was determined.

The participant rated the overall experience 8 out of 10 and said that the experience was enjoyable, but wouldn't want to fly an aircraft like this. The participant said that the aircraft was easier to control with the steering wheel, but it took a bit to get used to the different flight modes.

Pattern Flight

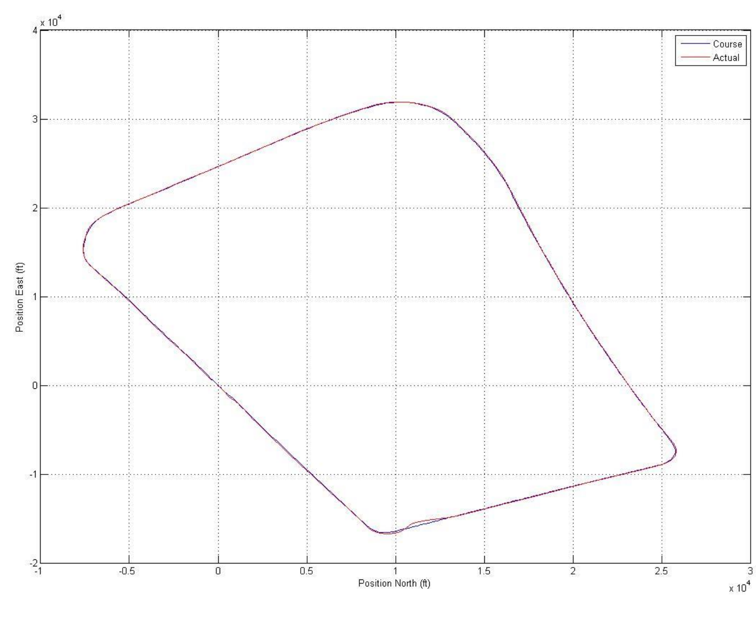


FIGURE 38: SP1 - PATTERN FLIGHT PATH IN TWO DIMENSIONS

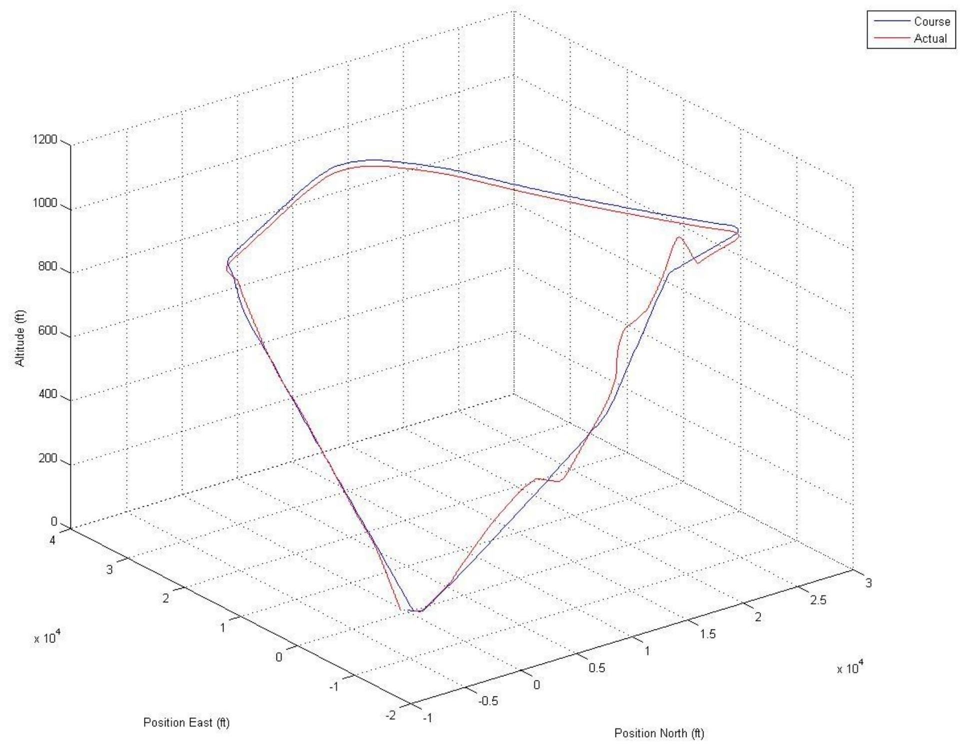


FIGURE 39: SP1 - PATTERN FLIGHT PATH IN THREE DIMENSIONS

It is clear from the above two figures that this participant had little difficulty maintaining the aircraft’s flight path with minimal difficulty controlling altitude. This is likely due to the adjustment to the flight modes. The participant was also able to control the aircraft with a very low pilot workload. Right off the bat, the steering wheel inputs were saturated only once to get back on course probably because of previous flight experience. It became increasingly clear that those without flight experience would overuse the steering wheel until they got used to the flight dynamics.

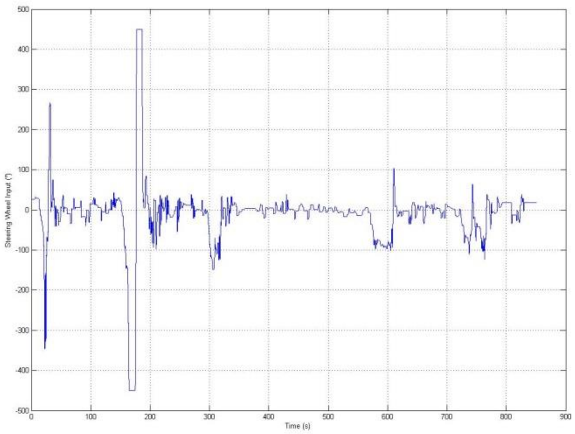


FIGURE 40: SP1 - STEERING WHEEL INPUT

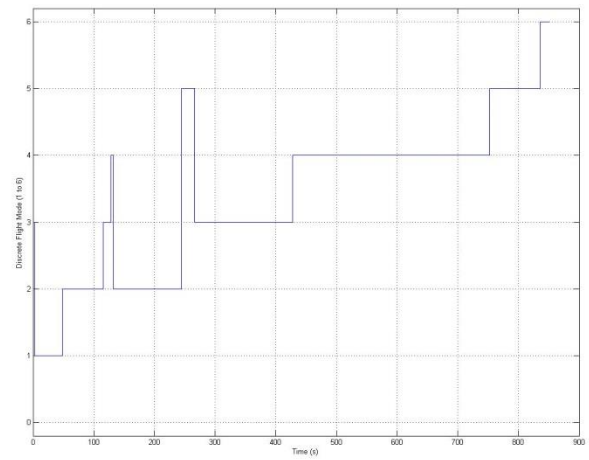


FIGURE 41: SP1 - SHIFTER INPUT

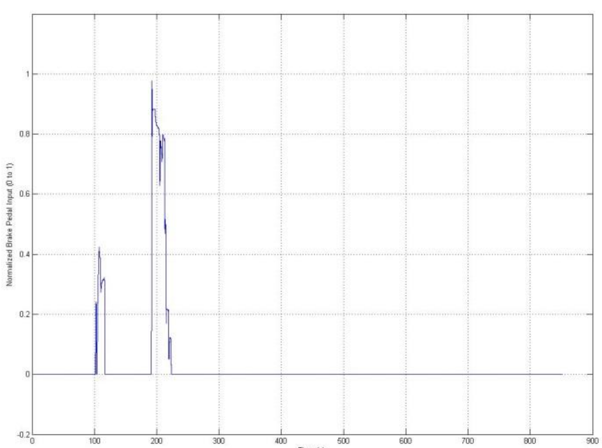


FIGURE 42: SP1 - BRAKE PEDAL INPUT

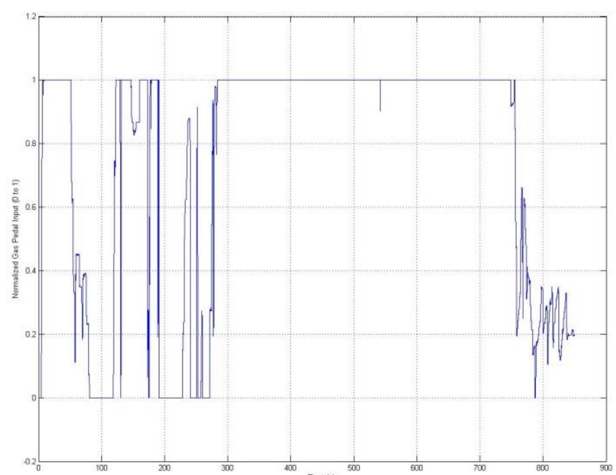


FIGURE 43: SP1 - GAS PEDAL INPUT

As you can see in Figure 43, the gas pedal was pushed during the entire cruise phase of flight. This was another typical occurrence with pilots which is to say that they wanted more control authority over the throttle and in general.

<u>San Carlos Flight</u>

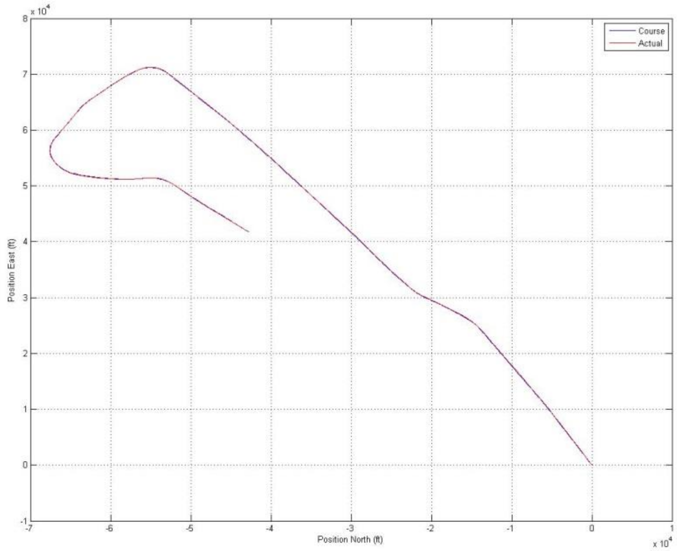


FIGURE 44: SP1 - SAN CARLOS FLIGHT IN TWO DIMENSIONS

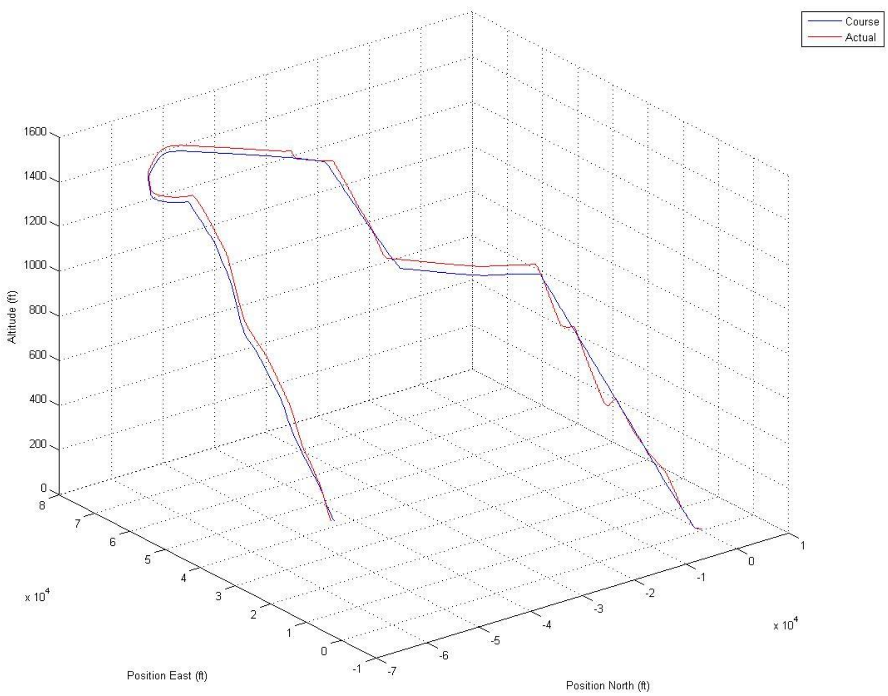


FIGURE 45: SP1 - SAN CARLOS FLIGHT IN THREE DIMENSIONS

It can be seen that the participant's control over altitude increased greatly along with a decrease in pilot workload as the familiarity with the flight modes increased.

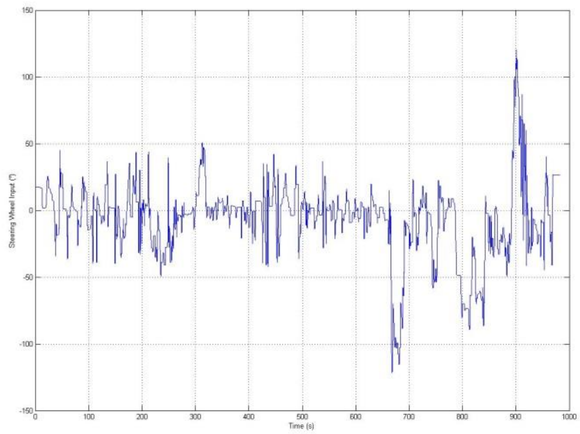


FIGURE 47: SP1 - STEERING WHEEL INPUT

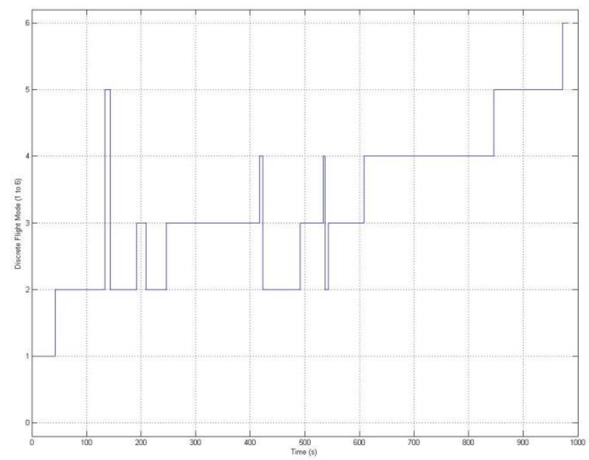


FIGURE 46: SP1 - SHIFTER INPUT

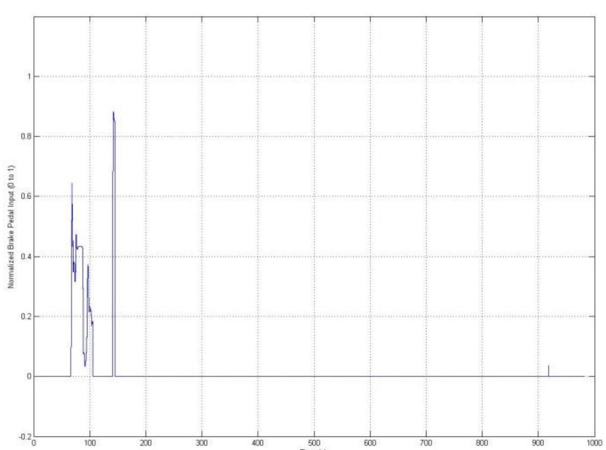


FIGURE 48: SP1 - BRAKE PEDAL INPUT

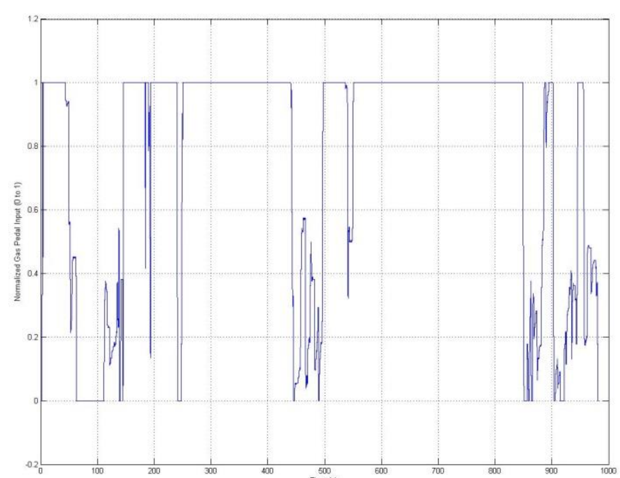


FIGURE 49: SP1 - GAS PEDAL INPUT

Oakland Flight

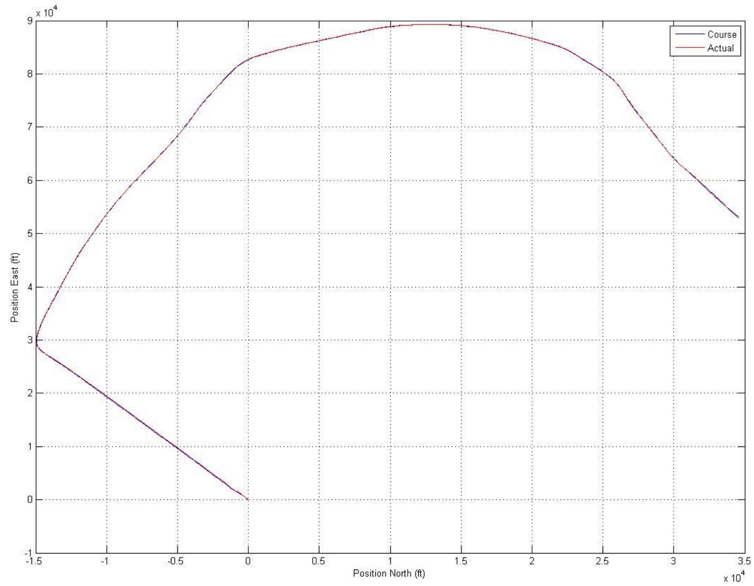


FIGURE 50: SP1 - OAKLAND FLIGHT PATH IN TWO DIMENSIONS

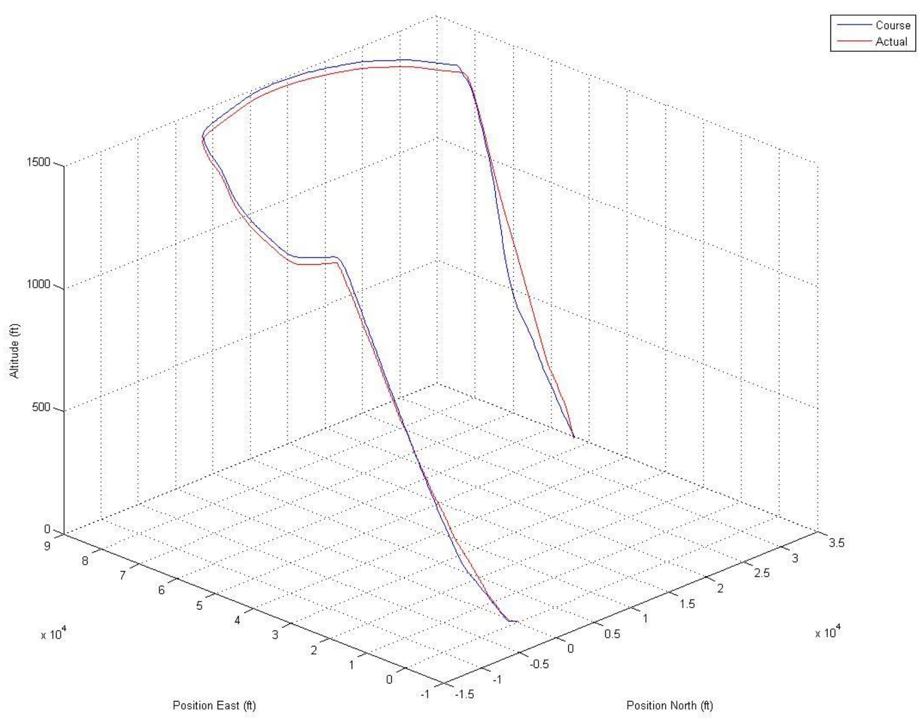


FIGURE 51: SP1 - OAKLAND FLIGHT PATH IN THREE DIMENSIONS

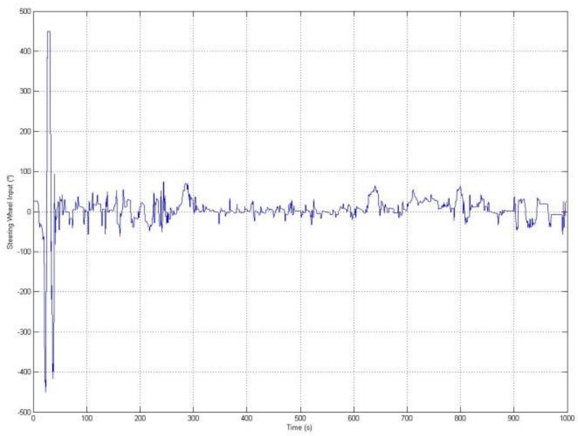


FIGURE 52: SP1 - STEERING WHEEL INPUT

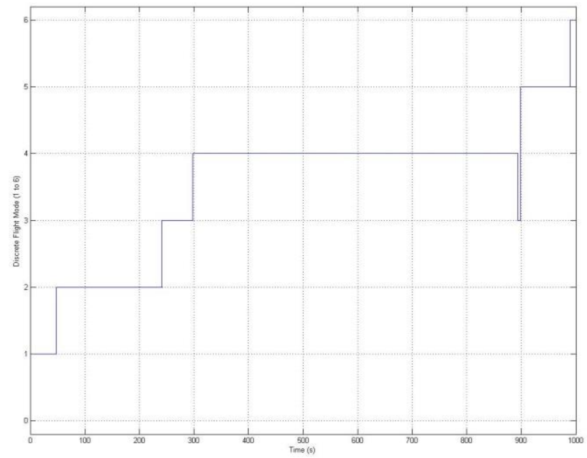


FIGURE 53: SP1 - SHIFTER INPUT

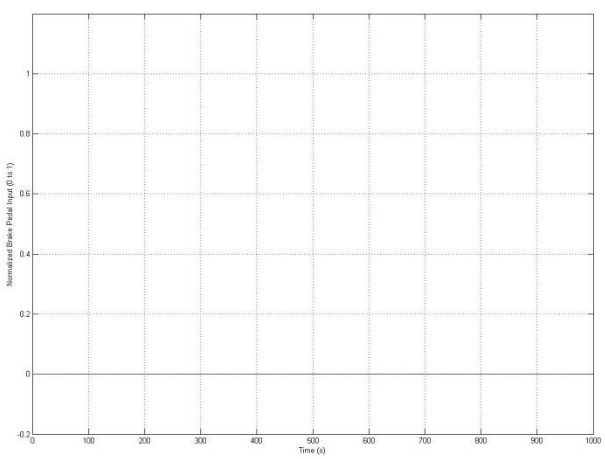


FIGURE 54: SP1 - BRAKE PEDAL INPUT

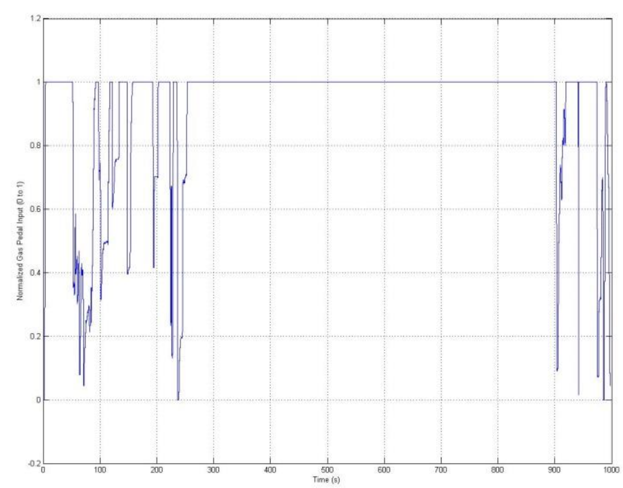


FIGURE 55: SP1 - GAS PEDAL INPUT

It is apparent that as this participant’s skill and familiarity with the control system increased, the trajectory tracking level increased along with a decrease in workload with one exception: the gas pedal was pressed throughout the majority of the flight. This could be remedied similarly to an automobile by adding a button to increase or decrease your power while in high speed cruise rather than using the gas or brake pedal for an extended period of time.

4.3. Experienced Pilots (XP)

There were 6 experienced pilots. The experienced pilot category represents pilots with at least 400 flight hours. This includes advanced student pilots who are seeking or already have commercial ratings as well as a few career pilots. A sample of the results from the experienced pilot category is provided below.

This experienced pilot subject was a 20 year old male with over 420 flight hours in numerous different types of aircraft including gliders, aerobatic, and high performance aircraft. This participant had commercial and instrument ratings as a pilot and had a driver's license for four years driving a car with a manual transmission. A score of 87.5 out of 100 was given with the modified SUS and a Cooper-Harper rating of 2 was determined.

This participant rated the overall experience 8 out of 10 and said that "it was easy to control and enjoyable, but I feel I have more control the traditional way of flying." It was noticed and stated that the control system appreciably reduced the pilot's workload which is valuable.

Pattern Flight

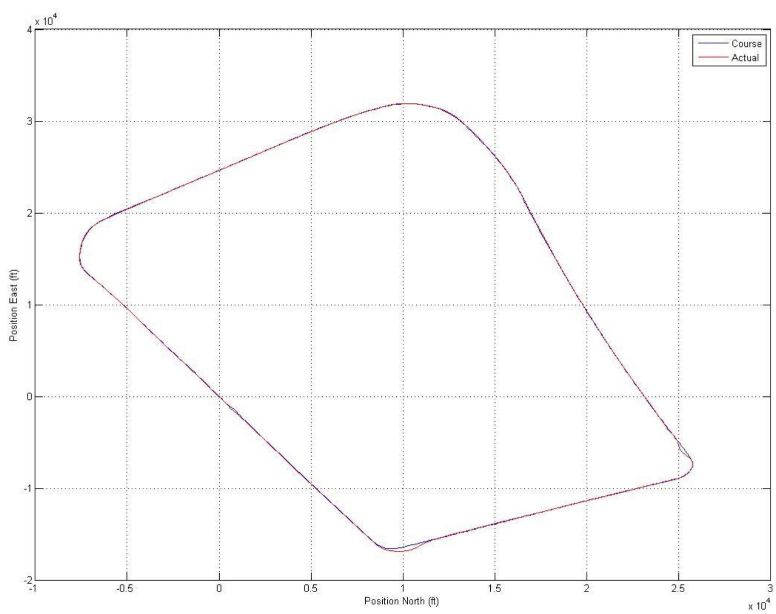


FIGURE 56: XP1 - PATTERN FLIGHT PATH IN TWO DIMENSIONS

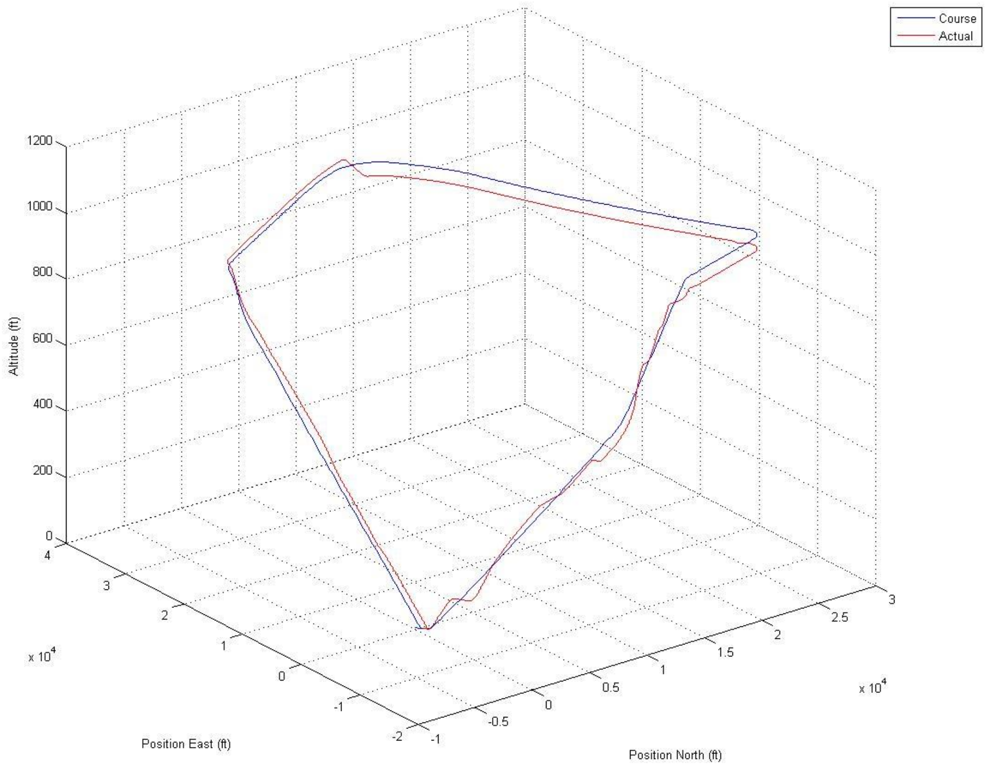


FIGURE 57: XP1 - PATTERN FLIGHT PATH IN THREE DIMENSIONS

Even though more control over the aircraft was desired as in traditional flying, this participant was able to control the aircraft very well with minimal workload.

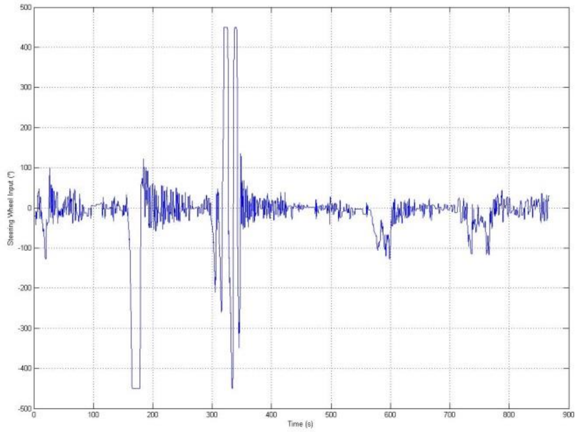


FIGURE 58: XP1 – STEERING WHEEL INPUT

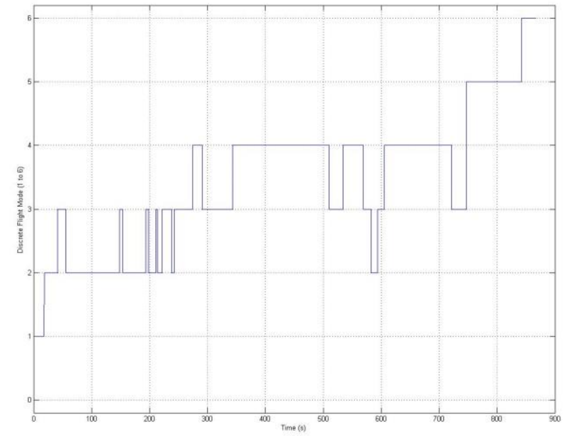


FIGURE 59: XP1 – SHIFTER INPUT

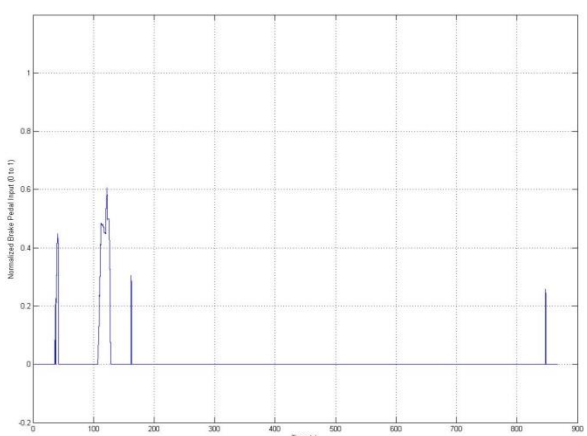


FIGURE 60: XP1 – BRAKE PEDAL INPUT

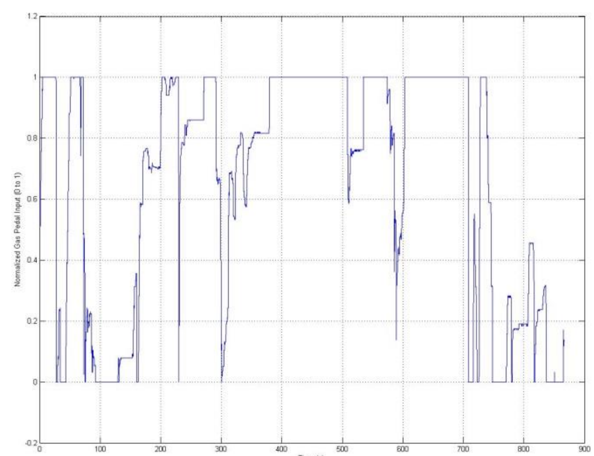


FIGURE 61: XP1 – GAS PEDAL INPUT

San Carlos Flight

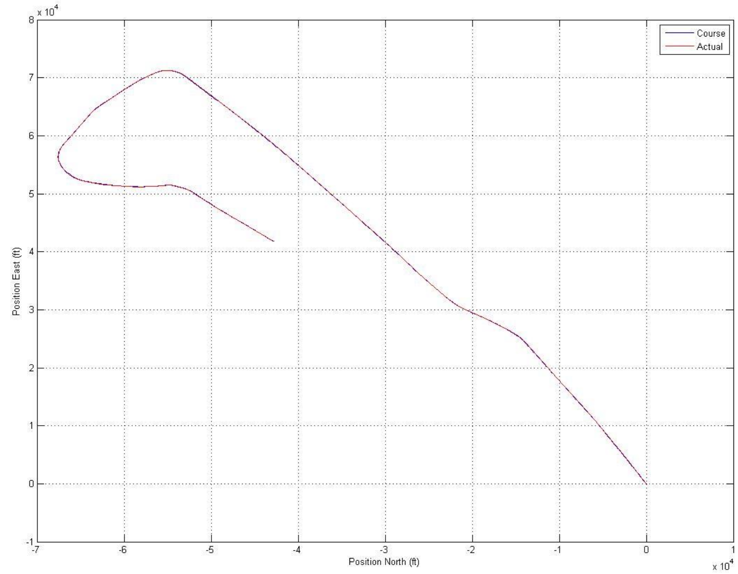


FIGURE 62: XP1 – SAN CARLOS FLIGHT PATH IN TWO DIMENSIONS

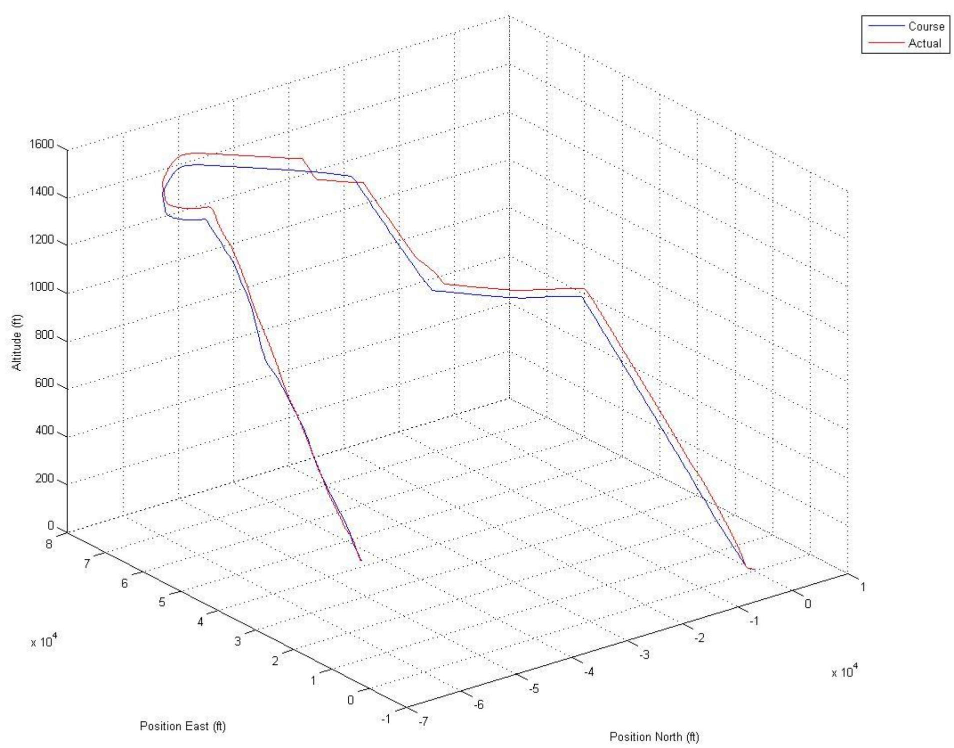


FIGURE 63: XP1 – SAN CARLOS FLIGHT PATH IN THREE DIMENSIONS

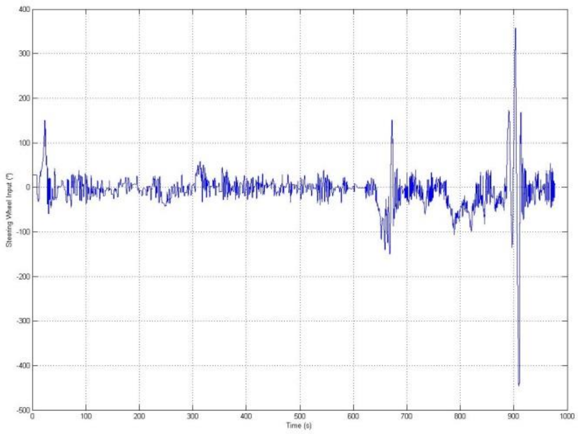


FIGURE 64: XP1 - STEERING WHEEL INPUT

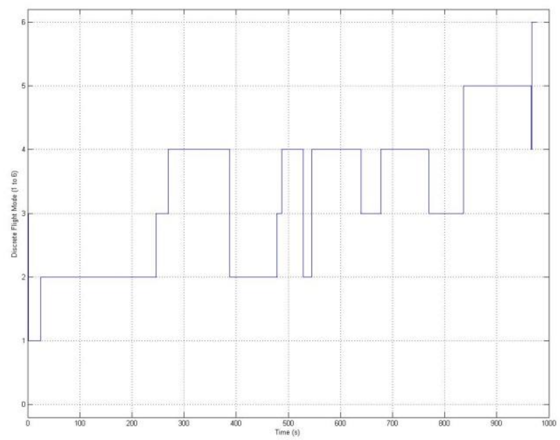


FIGURE 65: XP1 - SHIFTER INPUT

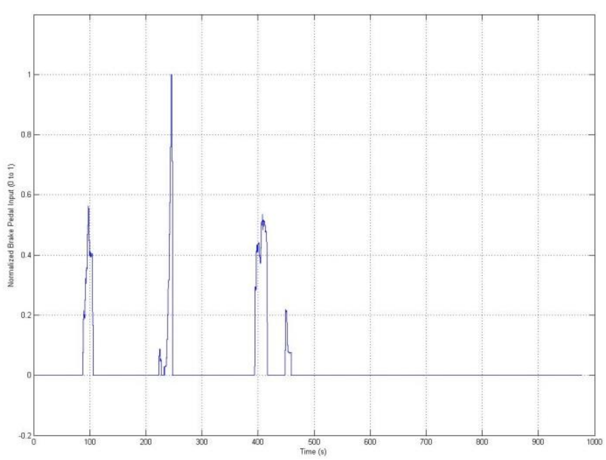


FIGURE 66: XP1 - BRAKE PEDAL INPUT

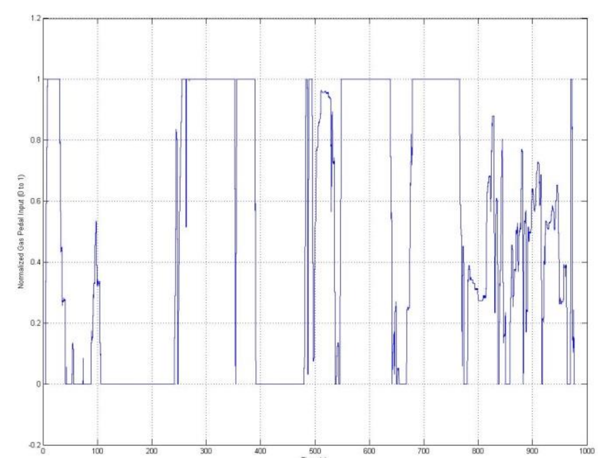


FIGURE 67: XP1 - GAS PEDAL INPUT

Oakland Flight

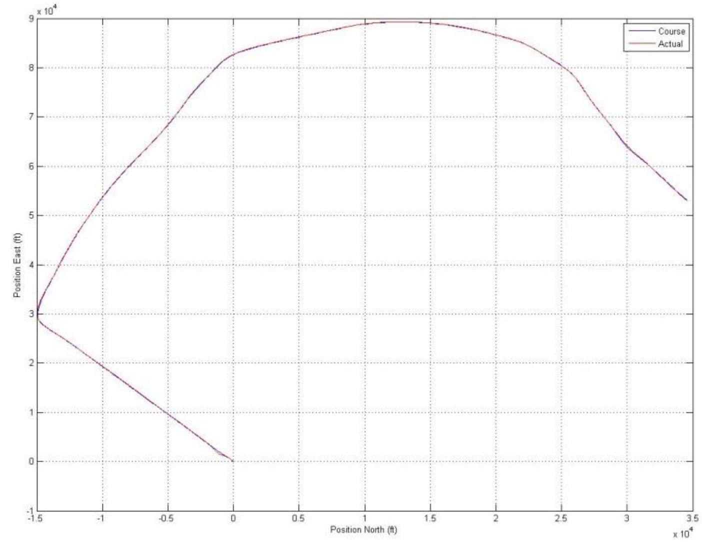


FIGURE 68: XP1 – OAKLAND FLIGHT PATH IN TWO DIMENSIONS

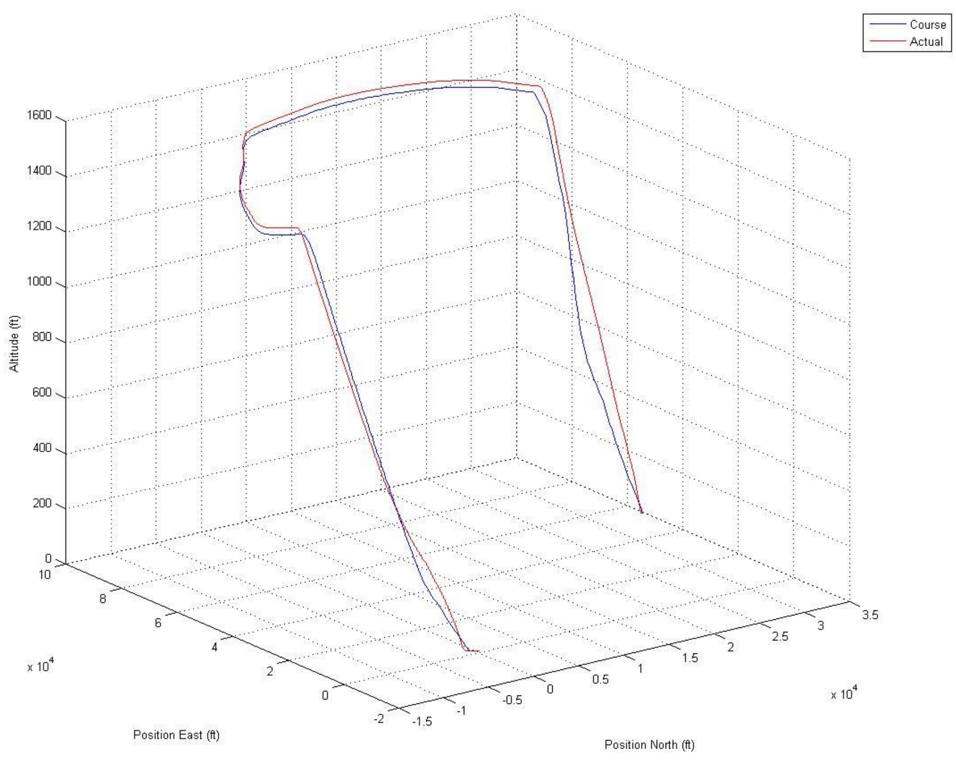
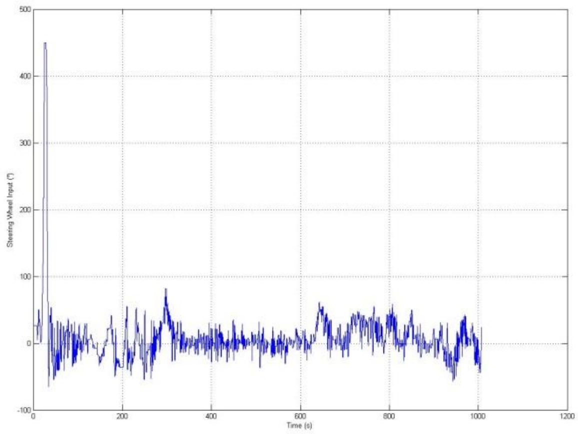


FIGURE 69: XP1 – OAKLAND FLIGHT PATH IN THREE DIMENSIONS



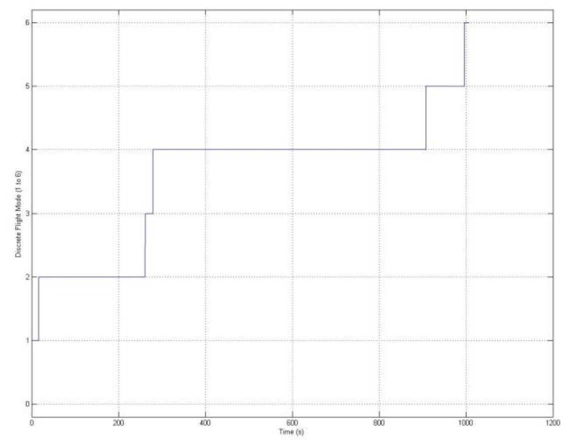
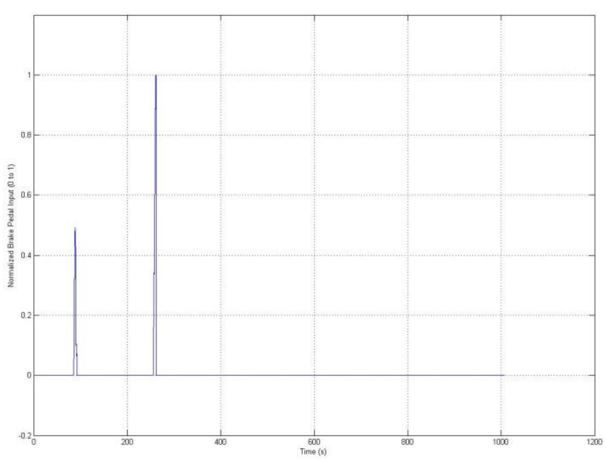


FIGURE 70: XP1 - STEERING WHEEL INPUT

FIGURE 71: XP1 - SHIFTER INPUT



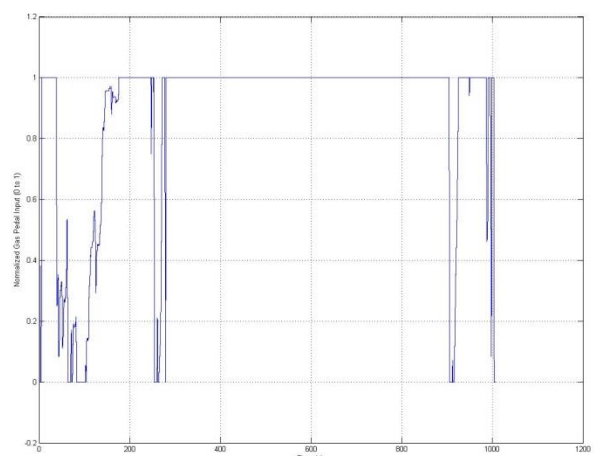


FIGURE 72: XP1 - BRAKE PEDAL INPUT

FIGURE 73: XP1 - GAS PEDAL INPUT

Clearly this participant was able to fly the aircraft easily without too much adjustment and very minimal pilot workload.

4.4. Comparison

A good measure of the effectiveness of this system is the comparison of the performance of an experienced pilot versus someone with no flight experience whatsoever. In this section, the trajectories and control inputs of the non-pilot, student pilot, and experienced pilot will be compared. The purpose is to show that in less than two hours, someone with no flight experience or knowledge of flight dynamics can operate an aircraft as safely and effectively as someone who has spent hundreds of hours in the air training. It is evident by inspection that the best measure of pilot workload is observed from the steering input of the subjects. For this reason, the only control input that will be compared is the steering input.

Pattern Flight

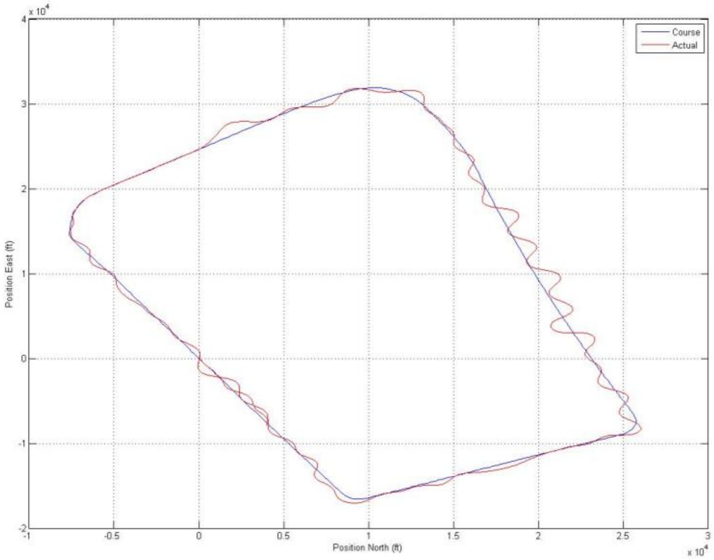


FIGURE 74: NON-PILOT 2D TRJECTORY

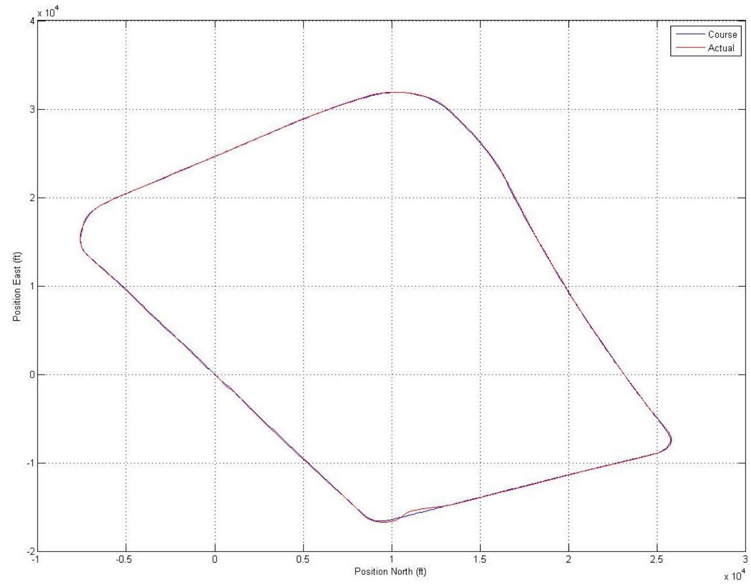


FIGURE 75: STUDENT PILOT 2D TRAJECTORY

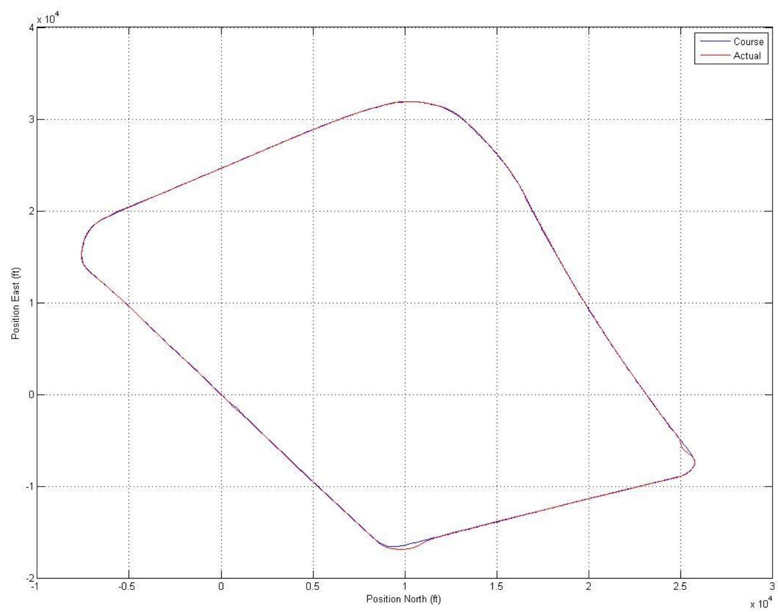


FIGURE 76: EXPERIENCED PILOT 2D TRAJECTORY

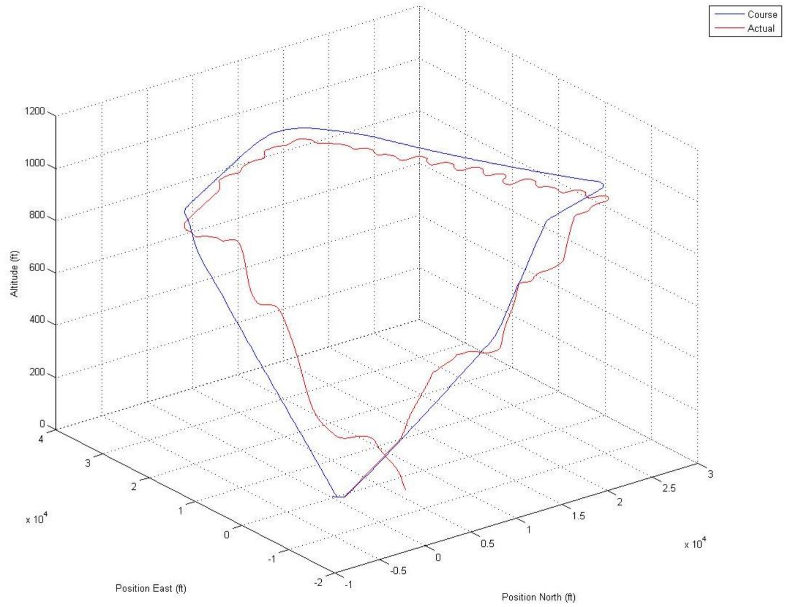


FIGURE 77: NON-PILOT 3D TRAJECTORY

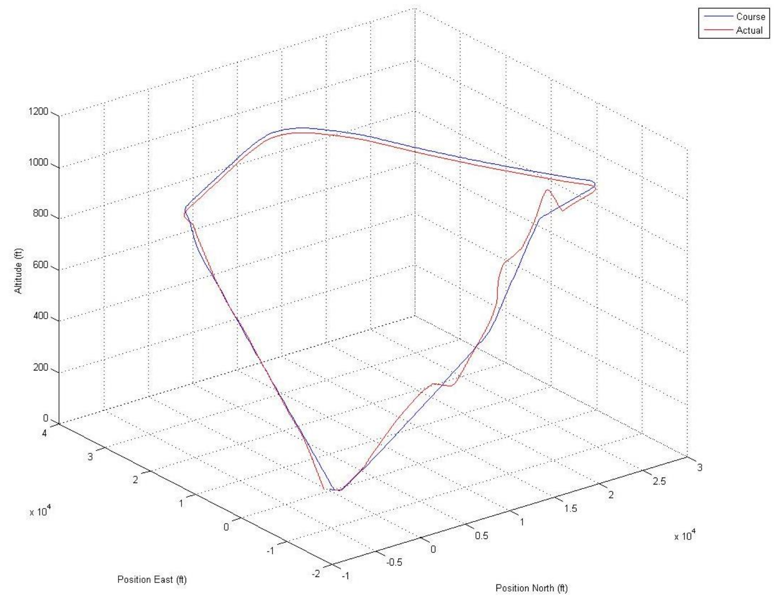


FIGURE 78: STUDENT PILOT 3D TRAJECTORY

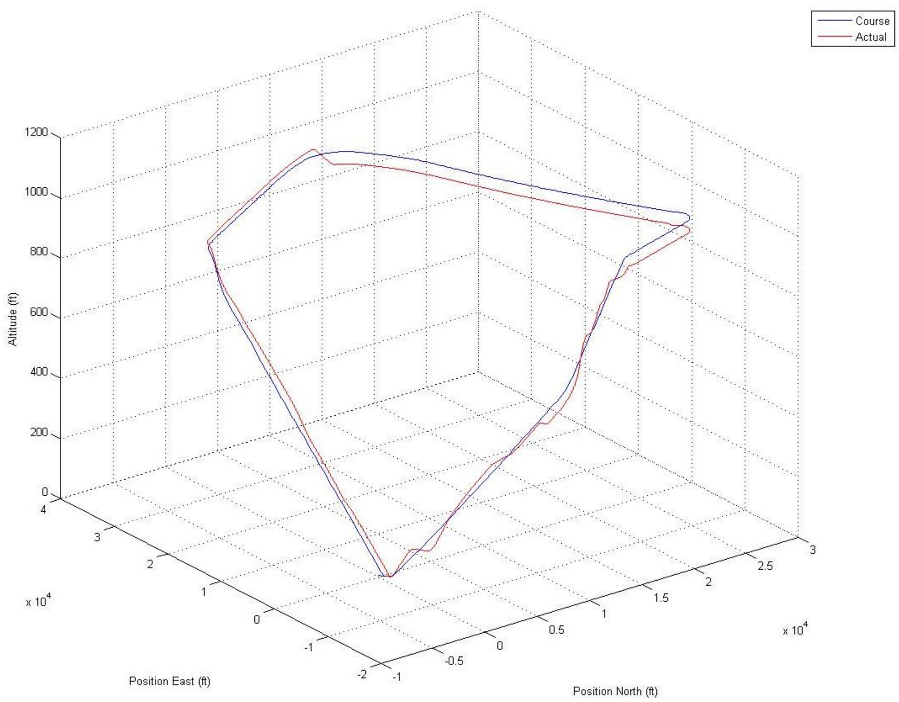


FIGURE 79: EXPERIENCED PILOT 3D TRAJECTORY

The R^2 value obtained for the non-pilot, student pilot, and experienced pilot pertaining to 2D trajectory tracking is 0.9622, 0.9876, and 0.9935 respectively.

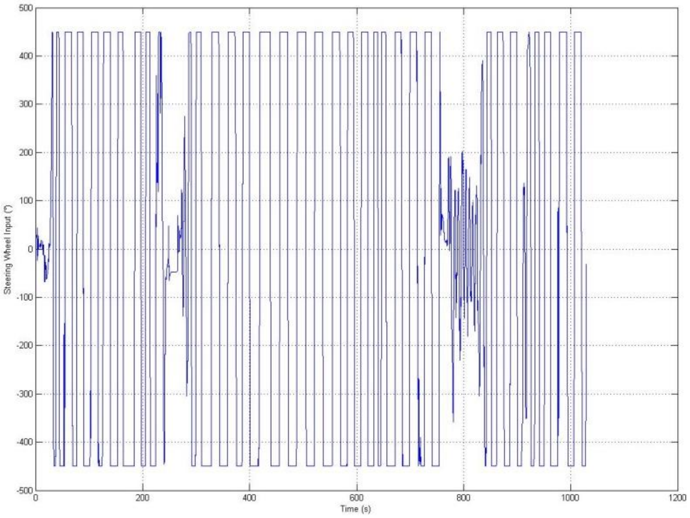


FIGURE 80: NON-PILOT STEERING INPUT

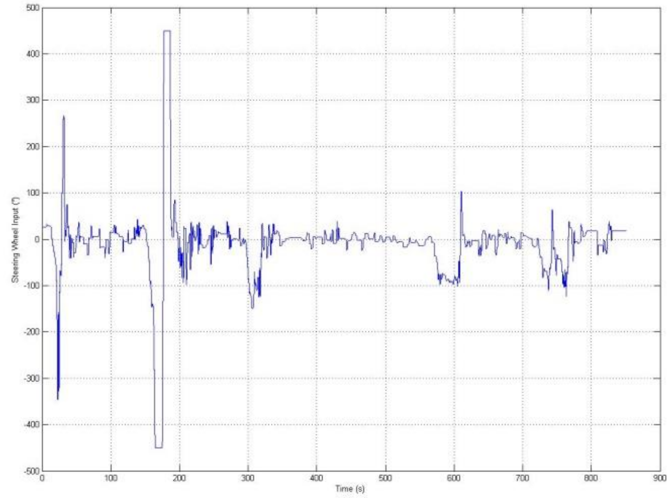


FIGURE 81: STUDENT PILOT STEERING INPUT

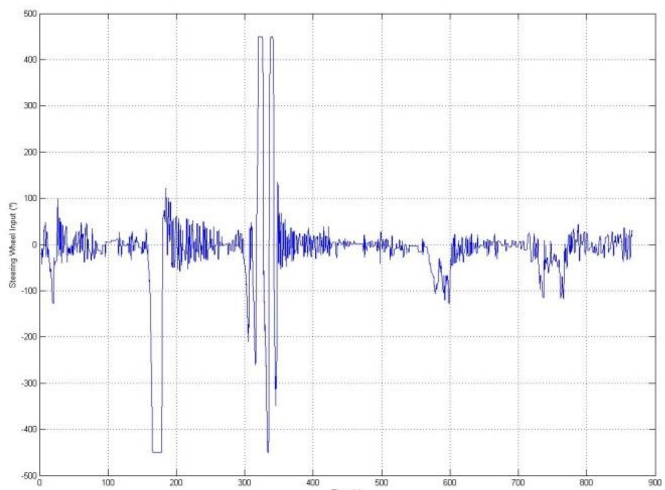


FIGURE 82: EXPERIENCED PILOT STEERING INPUT

As you can see from the first flight flown, the pattern flight, by the test subjects the non-pilot was having some trouble adjusting to flying the aircraft. That participant was able to manage altitude relatively well, but was having clear difficulties adjusting to tracking the prescribed trajectory. The non-pilot participant was turning the wheel all the way to the left or the right which is not typically how one drives so it is possible that this participant went into the test without trying to adapt driving skills to flying the aircraft. The student pilot had some trouble with altitude control at first, but was able to resolve that issue rather quickly. The experienced pilot didn't have any difficulty navigating the first mission.

San Carlos Flight

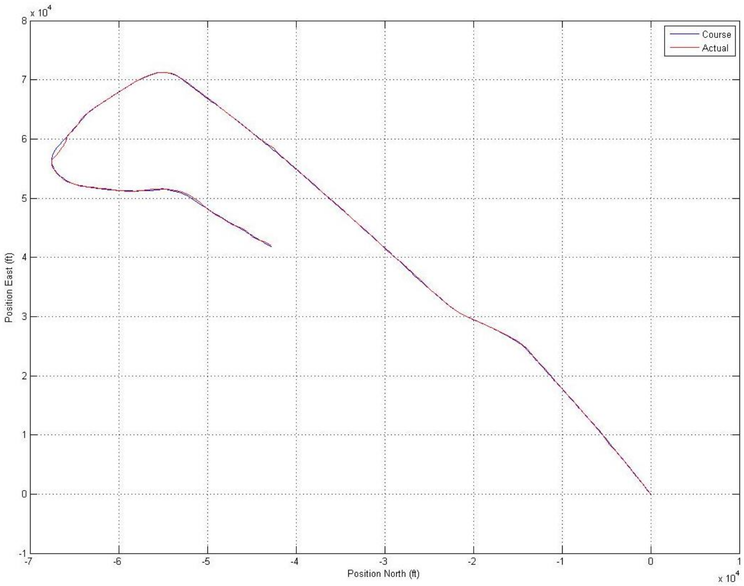


FIGURE 83: NON-PILOT 2D TRAJECTORY

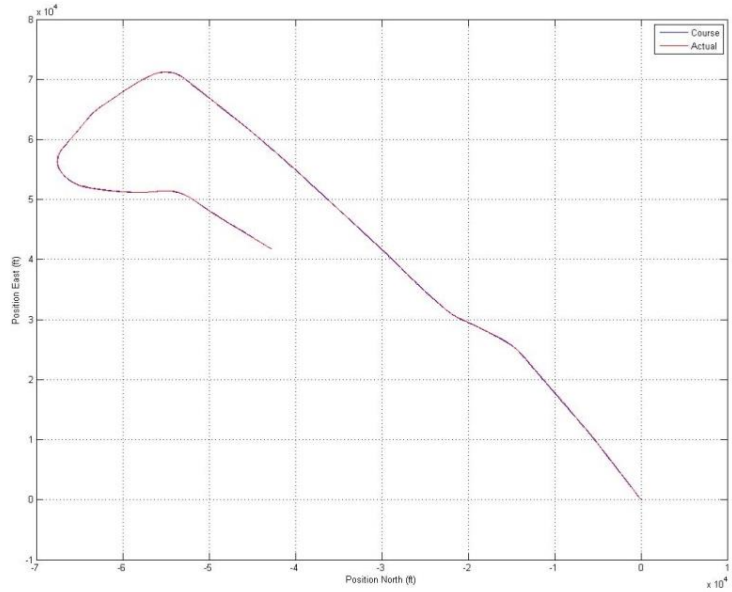


FIGURE 84: STUDENT PILOT 2D TRAJECTORY

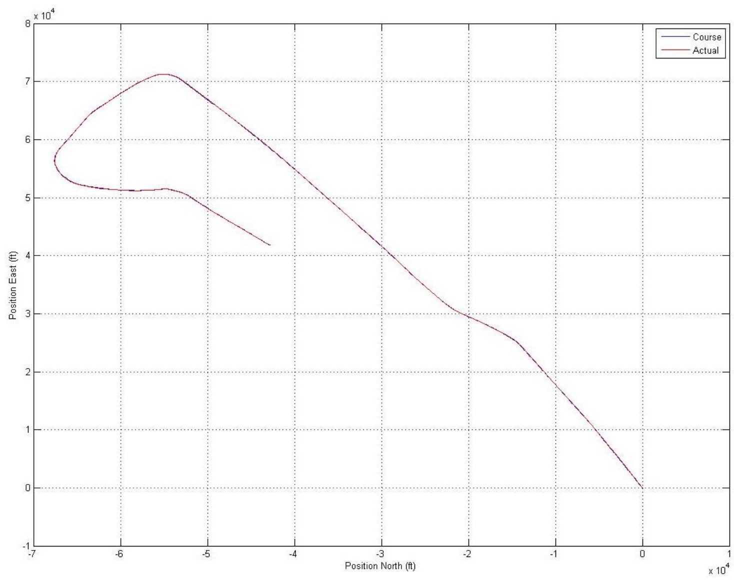


FIGURE 85: EXPERIENCED PILOT 2D TRAJECTORY

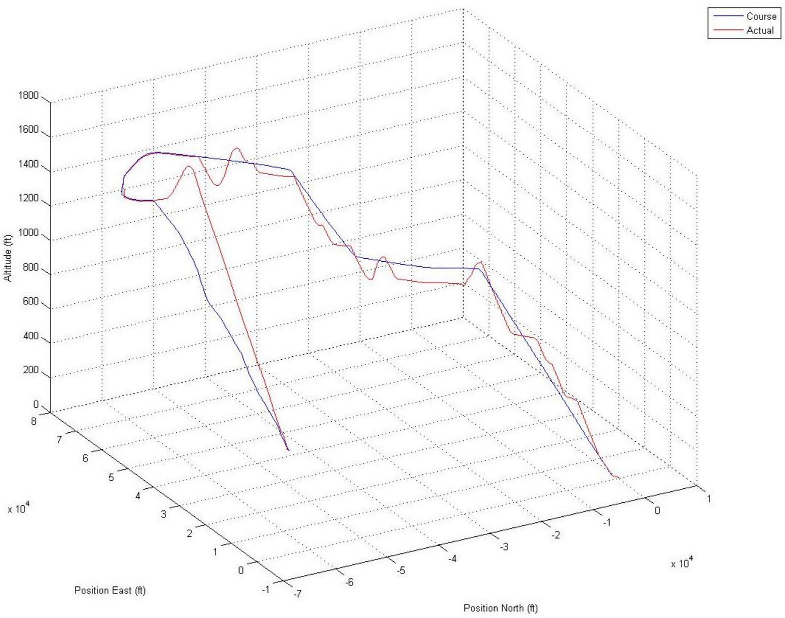


FIGURE 86: NON-PILOT 3D TRAJECTORY

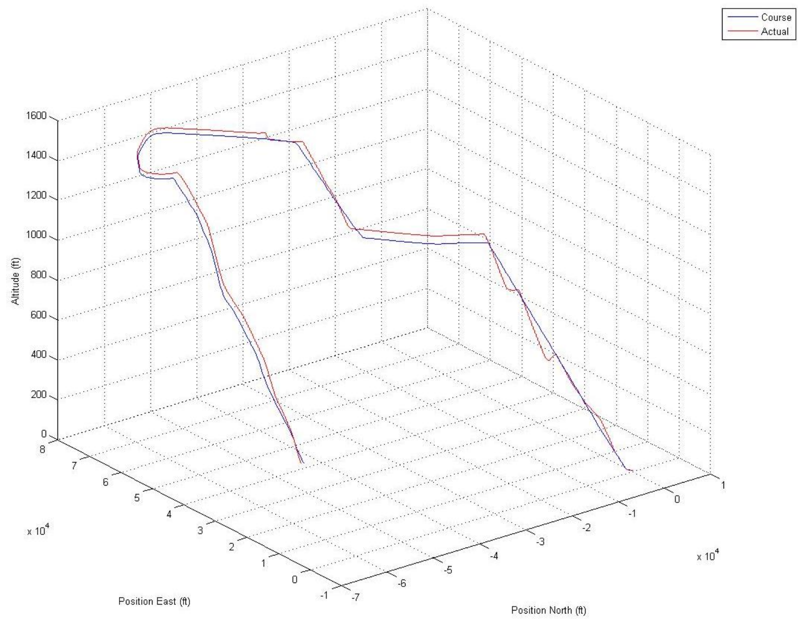


FIGURE 87: STUDENT PILOT 3D TRAJECTORY

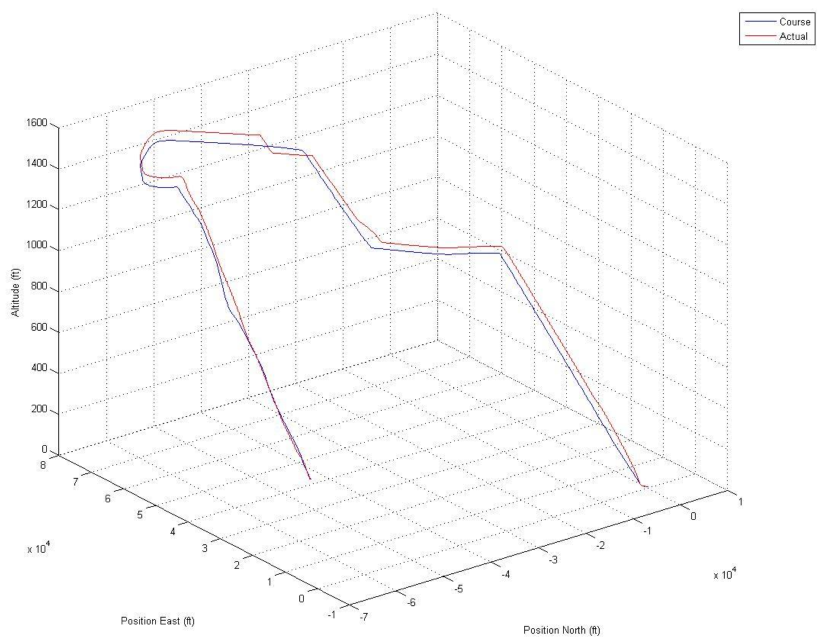


FIGURE 88: EXPERIENCED PILOT 3D TRAJECTORY

The R^2 value obtained for the non-pilot, student pilot, and experienced pilot pertaining to 2D trajectory tracking is 0.9963, 0.9977, and 0.9983 respectively.

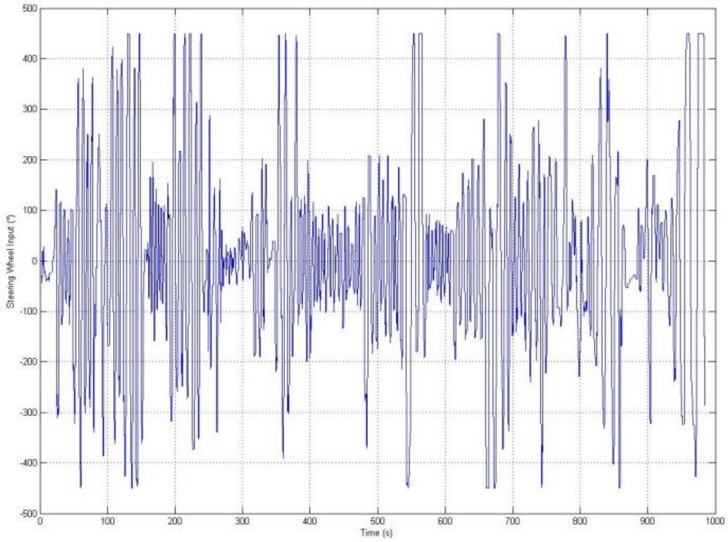


FIGURE 89: NON-PILOT STEERING INPUT

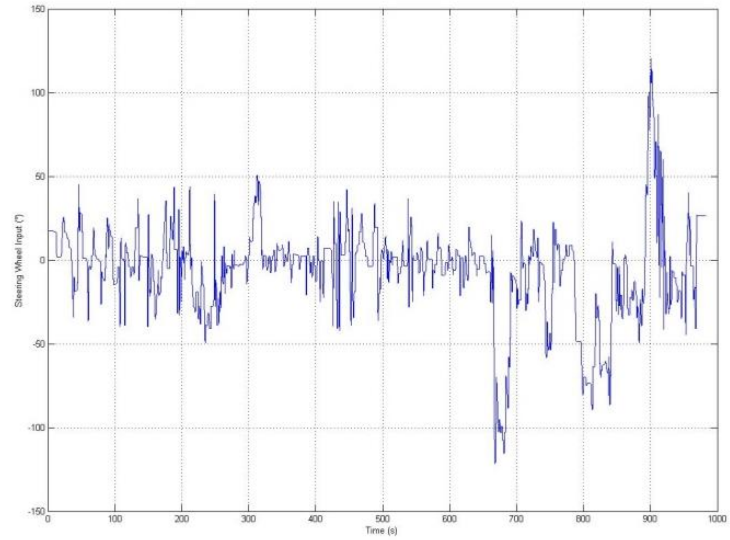


FIGURE 90: STUDENT PILOT STEERING INPUT

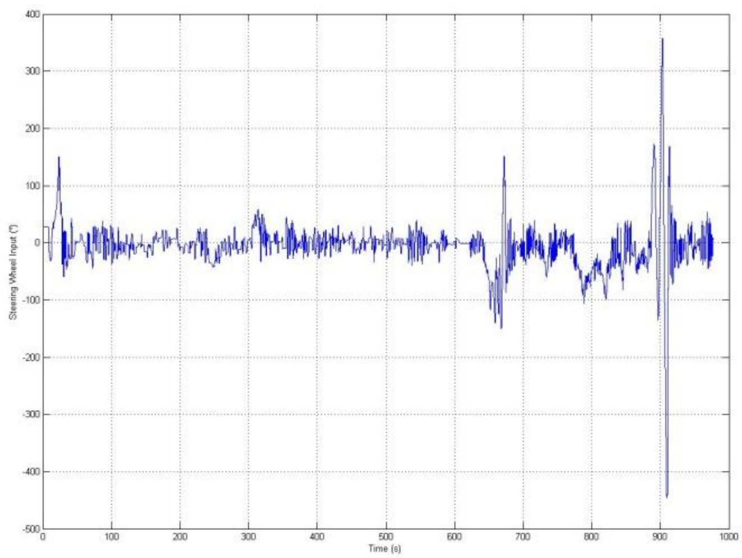


FIGURE 91: EXPERIENCED PILOT STEERING INPUT

As you can see clearly in the 2D trajectory, the non-pilot's ability to track the prescribed trajectory has greatly improved in this scenario. The pilot workload was still relatively high when compared with the workloads of the student and experienced pilots. Also, in this scenario, the non-pilot was still having trouble tracking the correct altitude whereas the student pilot's ability to track altitude has improved. The experienced pilot's performance improved as well.

Oakland Flight

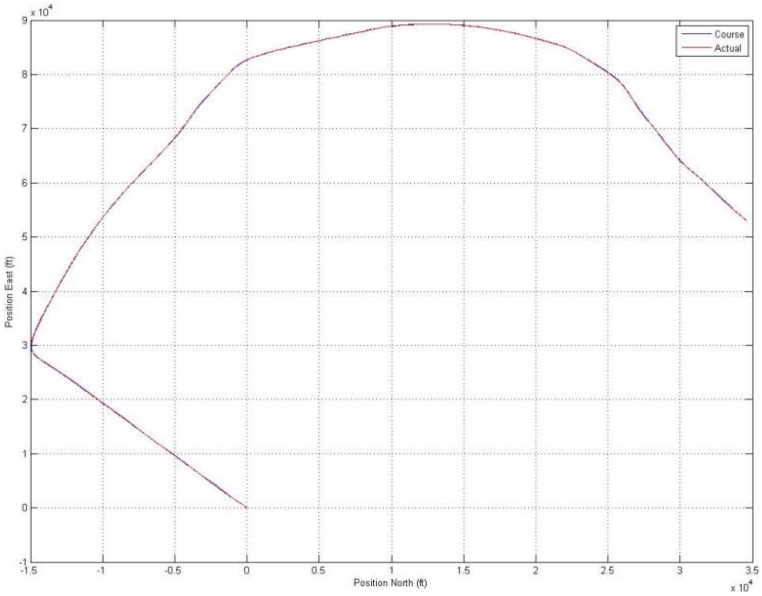


FIGURE 92: NON-PILOT 2D TRAJECTORY

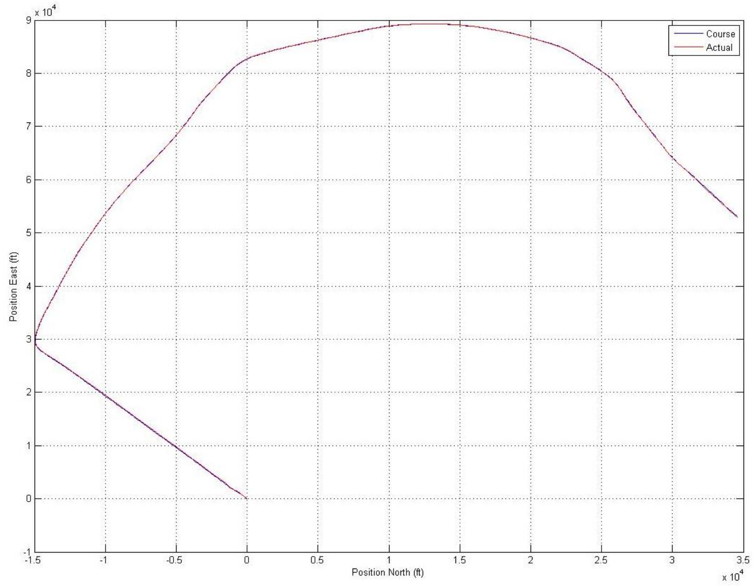


FIGURE 93: STUDENT PILOT 2D TRAJECTORY

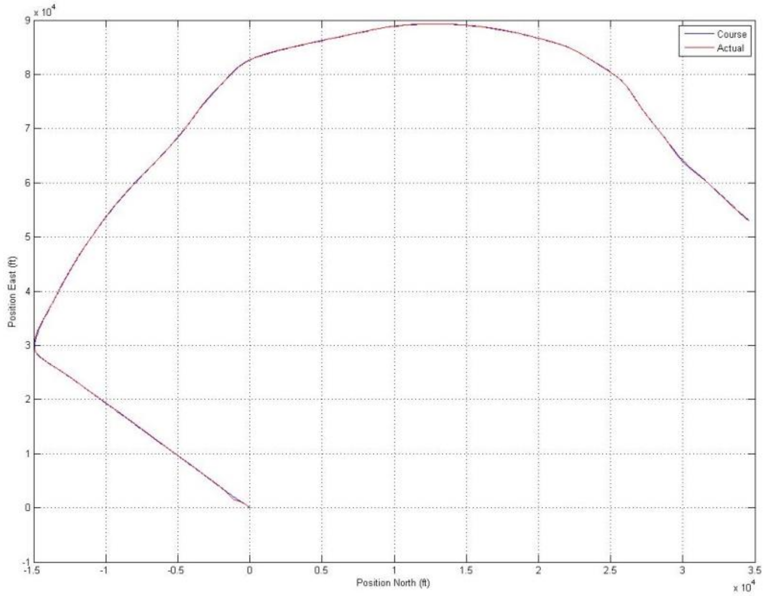


FIGURE 94: EXPERIENCED PILOT 2D TRAJECTORY

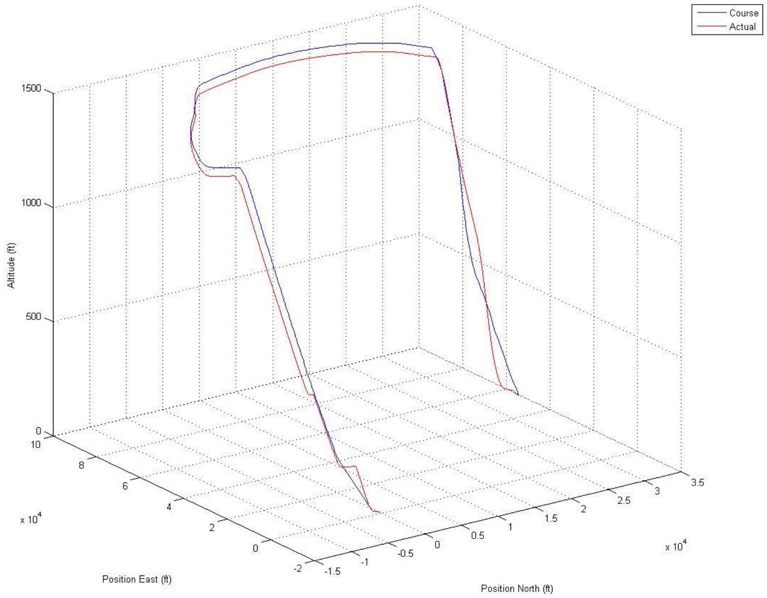


FIGURE 95: NON-PILOT 3D TRAJECTORY

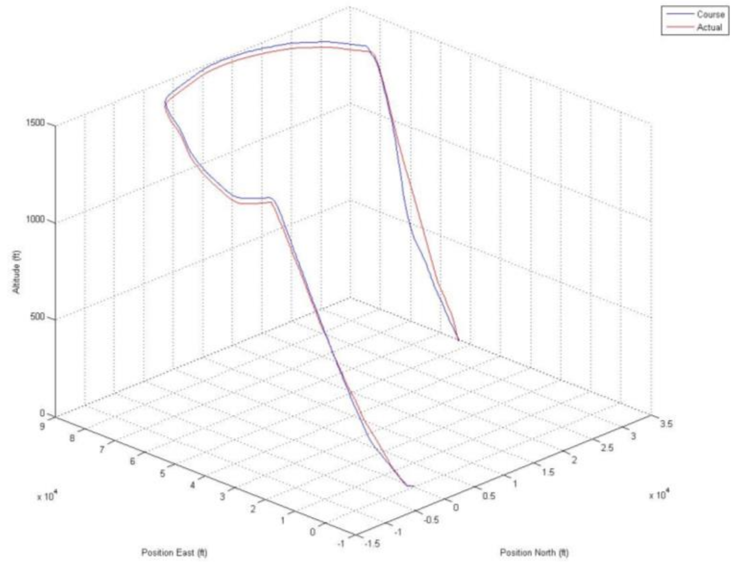


FIGURE 96: STUDENT PILOT 3D TRAJECTORY

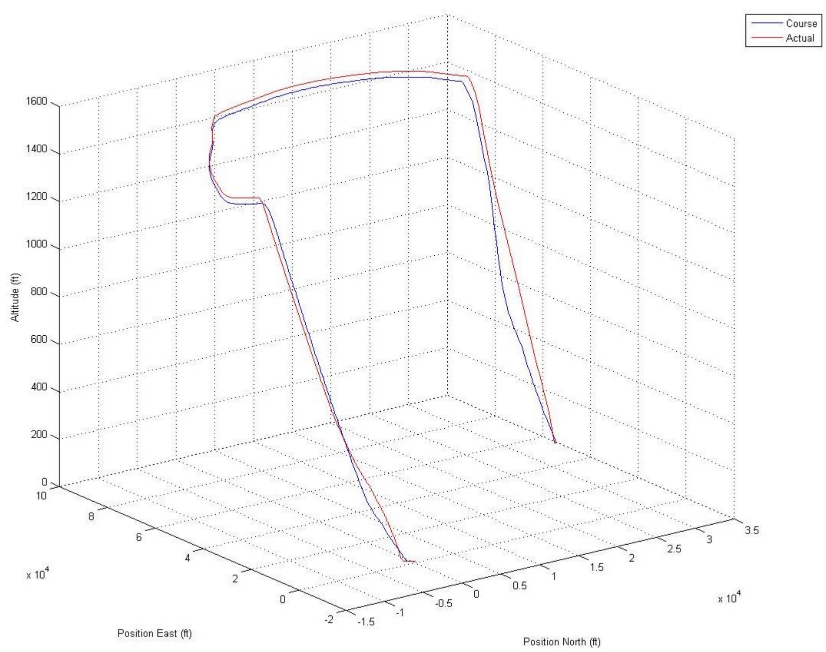


FIGURE 97: EXPERIENCED PILOT 3D TRAJECTORY

The R^2 value obtained for the non-pilot, student pilot, and experienced pilot pertaining to 2D trajectory tracking is 0.9993, 0.9987, and 0.9973 respectively. Numerically speaking, the non-pilot was able to out-perform the student and experienced pilots by this the third and final flight. To the naked eye, however, the performance of all three subjects is indistinguishable.

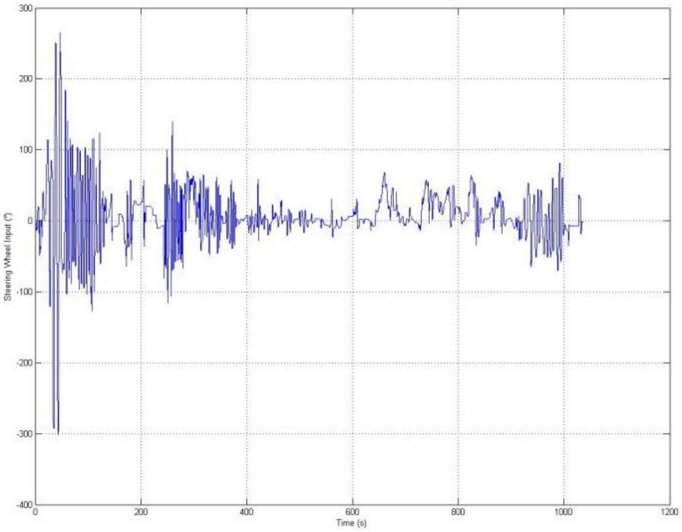


FIGURE 98: NON-PILOT STEERING INPUT

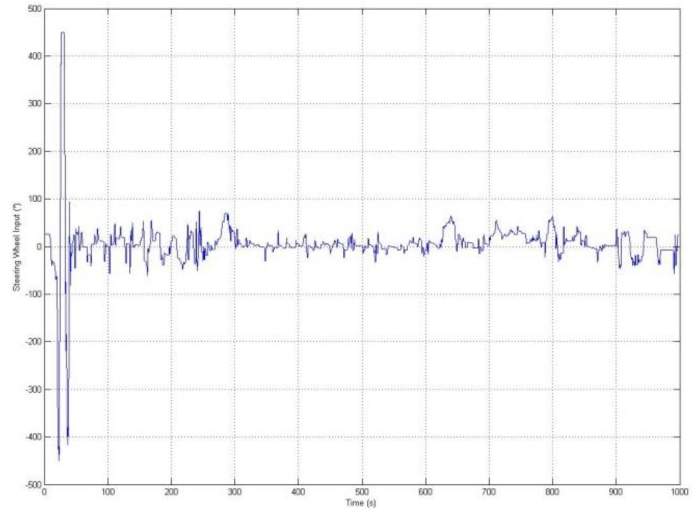


FIGURE 99: STUDENT PILOT STEERING INPUT

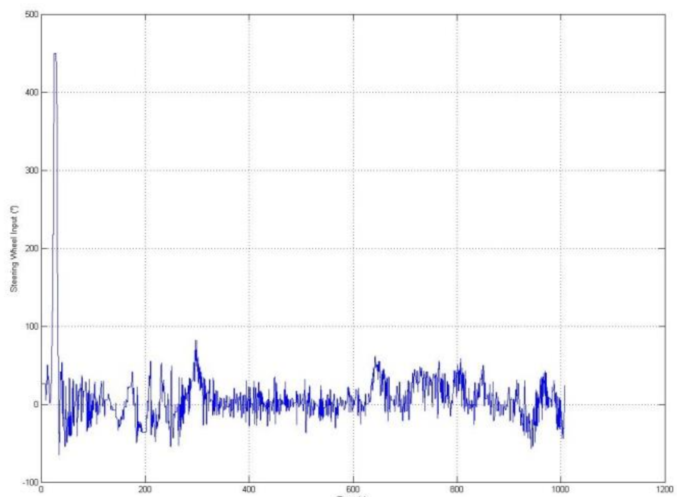


FIGURE 100: EXPERIENCED PILOT STEERING INPUT

By the third and final flight, the performance of all three test subjects is nearly indistinguishable when looking at the 2- and 3-D trajectories flown. It is also evident that the non-pilot's workload has decreased significantly from the pattern flight. At this point, less than two hours after flying for the first time, a person with no aviation knowledge or flight experience was able to track a prescribed trajectory as well as someone with hundreds of hours of flight experience and is training to be a professional pilot. Each of the participants was able to stay within 100 feet of the prescribed trajectory throughout the entire flight.

4.5. Statistics

There were about 20 participants split into the three main categories. Within each category, there were some over the age of forty. This was particularly true within the non-pilot category which bears relevance to the fact that these would primarily be the demographic to use a system such as this. In all cases however, nearly every participant was able to stay within the follow-me boxes with very little effort, even the non-pilots who've never flown a simulation and have no idea how to use typical aircraft controls. Using their knowledge of automobiles and everyday driving habits, there is a very shallow learning curve that just about anyone, even a teenager without a driver's license, can pick up quickly with minimal instruction or effort. The tables below will outline all of the participants' SUS and Cooper-Harper scores along with some relevant demographics. In the non-pilot and student pilot categories, there are some clear outliers that bring the SUS average score down and the Cooper-Harper average score up drastically. These can be chalked up to participants not clearly understanding the Cooper-Harper rating scale and/or exaggerating some of their negative views in the SUS. Regardless of the SUS or Cooper-Harper score for each test subject, they were all able to takeoff, navigate, and land safely without too much trouble making the system clearly usable with high level handling qualities.

TABLE 4: NON-PILOT STATISTICS

Category	Age	Gender	SUS	Cooper-Harper
NP	22	F	75	8
NP	50	M	85	2
NP	51	F	27.5	8
NP	15	F	85	2
NP	40	F	75	2
NP	69	F	40	4
NP	51	M	80	4
NP	47	F	25	5
NP	36	F	80	4
Average	-	-	63.61	4.33

TABLE 5: STUDENT PILOT STATISTICS

Category	Age	Gender	SUS	Cooper-Harper
SP	24	M	70	3
SP	18	F	80	2
SP	27	F	87.5	2
SP	36	M	42.5	5
SP	20	M	90	2
Average	-	-	74	2.8

TABLE 6: EXPERIENCED PILOT STATISTICS

Category	Age	Gender	SUS	Cooper-Harper
XP	34	M	97.5	2
XP	21	M	77.5	5
XP	22	M	87.5	2
XP	23	F	80	2
XP	25	M	80	3
XP	59	F	85	2
Average	-	-	84.58	2.67

5. CONCLUSION AND RECOMMENDATIONS

It is noteworthy that the experienced pilots had the best SUS scores and Cooper-Harper ratings even though every pilot inherently didn't actually like the control system because they felt that it took away from the actual flying experience as well as maneuverability. These results are very reliable because they come from individuals with a wealth of aviation knowledge who know exactly what should be judged when it comes to aircraft system usability and handling qualities. The fact that the experienced pilots had an average of about 85% on the system usability scale and just over 2.5 for Cooper-Harper rating is a validation of this system. Pilots with many thousands of hours combined have agreed that it is easy to learn and an effective way to get from point A to point B which is exactly the use intended for this system. The fact that none of the pilots would want an aircraft with these controls is not a surprise because flying is what they do for a living; they've been trained and already have the habits and muscle memory required to fly an aircraft traditionally. This system will be fantastic for the once or twice a month long distance commuters. They would only need to use their everyday driving habits to maintain their flying skills. It is also clear that people of all ages are able to pick up this ability with ease.

The comparison in section 4.4 in and of itself is a validation of the control system. Any person possessive of knowledge of driving an automobile can learn to pilot an aircraft in less than two hours of reading and simulation. The progression of the non-pilot's proficiency in trajectory tracking and altitude management speaks volumes to the efficacy of this control system. It does require somewhat of a learning curve when it comes to flight dynamics and trajectory tracking in an aircraft, but with little practice this hurdle is easily overcome as demonstrated.

From the 2D plots of the flights for the non-pilot, an R^2 value was calculated to quantify how well the course was tracked. The values for the pattern, San Carlos, and Oakland flights are 0.9622, 0.9963, and 0.9993 respectively. This is a significant increase in the subject's ability to stay on the prescribed course. A more tangible measure used to validate the control system is the maximum deviation from the prescribed course in feet. In the first flight, the subject strayed by up to 1390 feet from the follow-me boxes. That performance would not be acceptable for safe operation. In the following two flights however, the maximum deviation decreased to 590 feet during the San Carlos flight and finally to less than 100 feet throughout the entire flight from

SFO to Oakland. The percent difference of the maximum deviations from the pattern and Oakland flights is 173%, a significant indicator of the shallow learning curve for these controls.

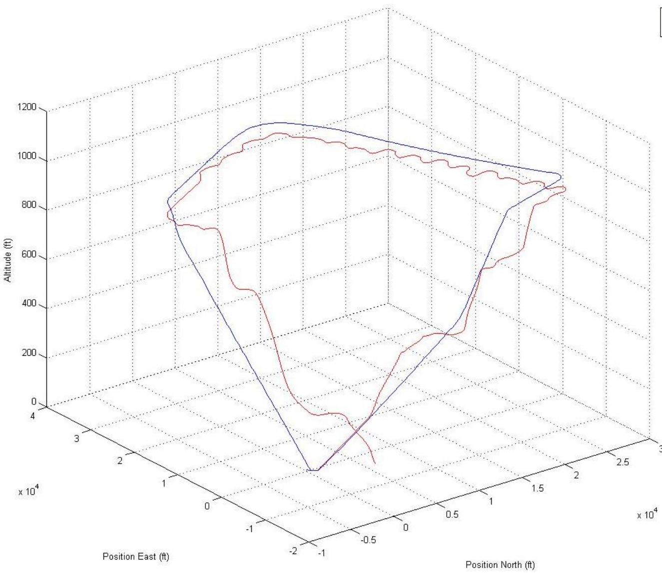


FIGURE 101: NON-PILOT PATTERN TRAJECTORY

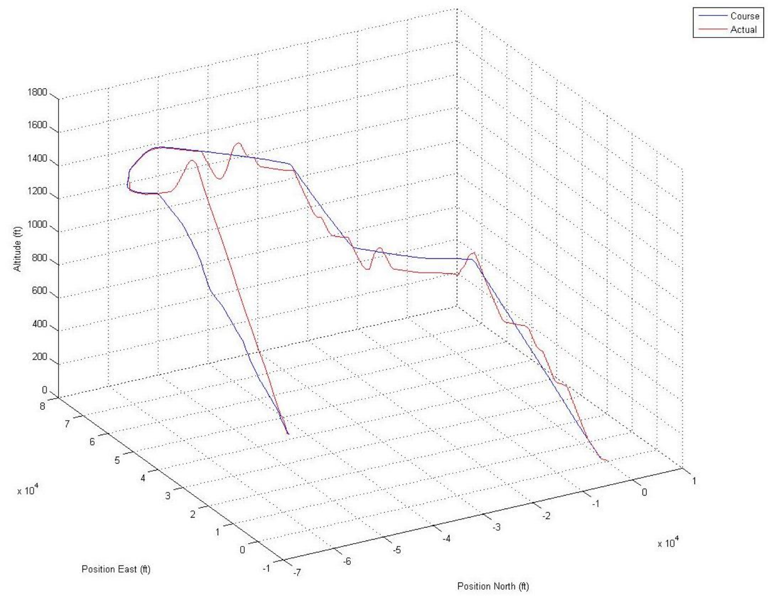


FIGURE 102: NON-PILOT SAN CARLOS TRAJECTORY

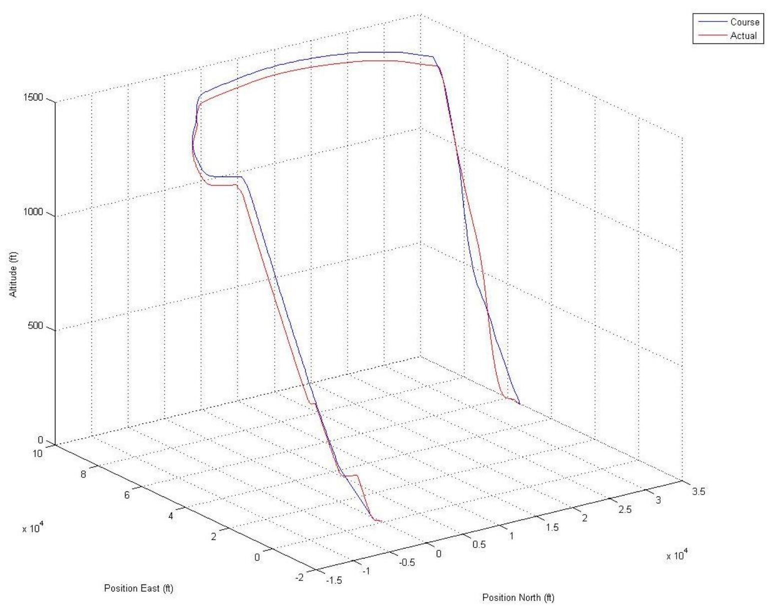


FIGURE 103: NON-PILOT OAKLAND TRAJECTORY

The progression of this test subject's proficiency is a validation of the shallow learning curve required to operate an aircraft with this control system. The figures below display the pilot's steering workload.

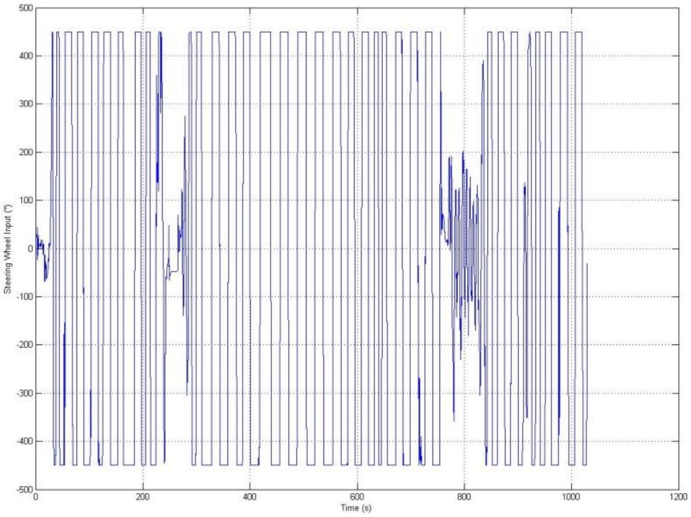


FIGURE 104: NON-PILOT PATTERN STEERING INPUT

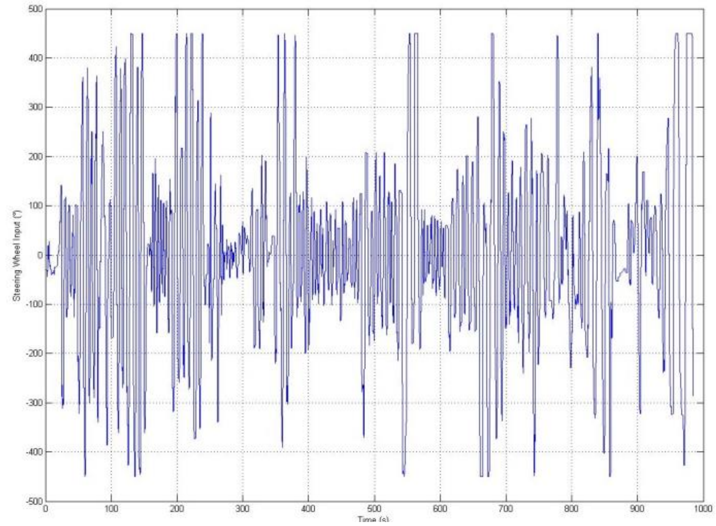


FIGURE 105: NON-PILOT SAN CARLOS STEERING INPUT

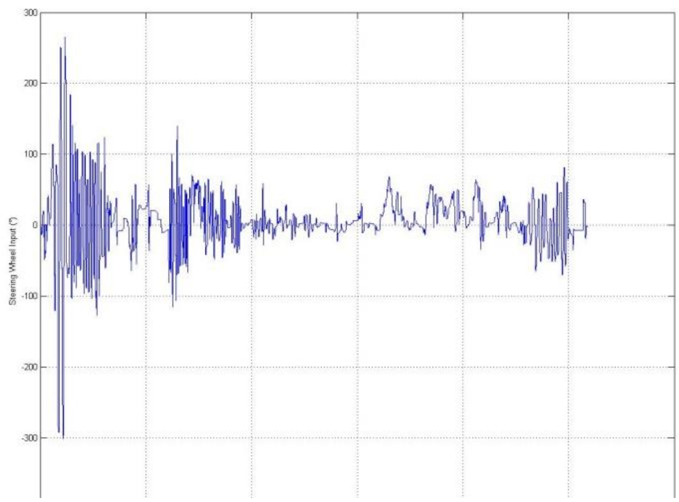


FIGURE 106: NON-PILOT OAKLAND STEERING INPUT

An important, burning question that needs to be answered is, “does having knowledge of driving a car actually assist in learning how to fly an aircraft with this control system?” Yes, this particular test subject alone proves that without aviation knowledge and with the knowledge of driving an automobile that one can learn to fly an aircraft with this control system with ease. The progression from an almost zigzag trajectory to a smooth, precise mission flown by the third scenario is a testament to the control system’s effectiveness. The progression of the reduction in pilot workload shown above is also proof of the effectiveness of the control system. With little practice, the participant did not have to turn the wheel more than ±100° to complete the mission.

As shown in the comparison of the test subjects' performance in section 4.4, the non-pilot's performance was nearly identical to the student and experienced pilots' performance when it came to trajectory tracking, maximum deviation from the given trajectory, and pilot workload. For all three participants, by the third and final flight, they didn't have to turn the steering wheel more than ±100° for the majority of the mission and the 2-D overlay of their trajectory versus the prescribed trajectory match almost perfectly. It all boils down to the efficiency and effectiveness of the control system. Each test subject was able to follow the prescribed trajectory with minimal pilot workload by the third scenario.

5.1. Future Work

Many man hours have been invested in the development of this control system. It is highly recommended that this system be further developed and tested with a new group of test subjects. There are many portions of this control system that can be improved upon such as:

- The development of the auto-flare capabilities to test actual landing scenarios.
- Development of engine-out mitigations for the control system (for single and multi-engine aircraft).
- Consider other risks that could be mitigated by this control system.
- For modes that require two LQR feedback loops, work on reducing this to one feedback loop for optimal control design.
- Taking qualitative feedback and integrating suggestions into the control system such as:
    - During cruise modes, have a button that would allow the pilot to have the capability to change altitudes discretely.
    - Also during cruise, give the pilot the ability to increase or decrease power without using gas/brake pedals similar to an automobile's cruise control.
- Further develop the introduction power point or create a brief instructional video for more clear instructions on the use of the control system.
- Provide a brief flight dynamics lesson at least on trajectory tracking in an aircraft for those unfamiliar with it. This seemed to be the biggest hurdle for non-pilots to overcome.

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APPENDIX A – CONSENT FORM

CONSENT FORM

Embry-Riddle Aeronautical University

I consent to participating in the research project entitled:

Mapping Automotive Controls to a General Aviation Aircraft

The principle investigator of the study is:

Advisor: Dr. Richard 'Pat' Anderson
Graduate Students: Christopher Carvalho & Kashif Ali

I understand that I will be participating in this study to the following extent. I will be briefed by power point and a brief video as to how to operate the simulation. I will operate the simulation under three different scenarios. Following these scenarios, I will fill out the provided survey to the best of my ability and answer the questions fully without consequence. If extra credit has been offered, I acknowledge that if I do not complete the study including the provided survey, I may forfeit the extra credit.

The individual above, or their research assistants, have explained the purpose of the study, the procedures to be followed, and the expected duration of my participation. Possible benefits of the study have been described, as have alternative procedures, if such procedures are applicable and available.

I acknowledge that I have had the opportunity to obtain additional information regarding the study and that any questions I have raised have been answered to my full satisfaction. Furthermore, I understand that I am free to withdraw consent at any time and to discontinue participation in the study without prejudice to me.

Finally, I acknowledge that I have read and fully understand the consent form. I sign it freely and voluntarily. A copy has been given to me.

Date: ______________________________

Name (please print): ____
(Participant)

Signed: ____
(Participant)

Signed: ____

APPENDIX B – USABILITY SURVEY

General Aircraft with Automotive Controls Usability Survey

The success of this survey depends upon your contribution, so it is important that you answer questions as honestly as you can. There are no right or wrong answers, and often the first answer that comes to mind is best. **Individual responses are absolutely confidential.**

Part I -Background Information/General Questions.

__ Age __ Gender (M/ F) __ Are you a Pilot? (Y/ N) ________ If Yes, how many hours?

If a pilot, what ratings do you possess and which aircraft have you flown?___________________________

____

Do you have previous experience flying aircraft simulators (even video games)? (Y/N) __

If yes, please specify. ____

Are you familiar with typical aircraft controls? (Y/N) __

If yes, to what extent? ____

____

Do you have a driver's license? (Y/N) __ If yes, for how many years? ___

Do you own a car? (Y/N)? __ If yes, does it have a manual or automatic transmission? _____________

If you own a car, what is the make and model? ____

Would you purchase a small aircraft with these controls? (Y/N) __

Part II –Pilot Views: This portion of the questionnaire asks you to express your perceptions of the simulation. Please answer by writing a number beside each item from the corresponding scale.

1 Very Low	2 Low	3 Adequate	4 High	5 Very High

A. Please evaluate your level of ***satisfaction*** with these different aspects of your experience.

____1. Quality of Hardware Familiarization Power point

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____2. Clarity of Hardware Familiarization Power point

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____3. Definition of goals

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____4. Shift Modes

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____5. Controllability

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____6. Ease of shifting

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____7. Ground Handling

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____8. Take-off Handling

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____9. Climb Handling

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____10. Cruise Handling

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____11. Descent Handling

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

____12. Landing Handling

1 - Very Low	2 - Low	3 - Adequate	4 - High	5 - Very High

B. Please respond to the following system usability statements by writing a number beside each item using the following scale.

1 Disagree Strongly	2 Disagree Slightly	3 Neutral	4 Agree Slightly	5 Agree Strongly

____1. I think that I would like to use this frequently.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____2. I found it unnecessarily complex.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____3. I thought it was easy and intuitive to control.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____4. I think that I would need support and additional training.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____5. I found the various flight modes were well integrated.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____6. I thought there was too much inconsistency with how it was controlled.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____7. I would imagine that most people would learn to use this very quickly.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____8. I found it very awkward to control.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____9. I felt confident during the entire flight.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____10. I needed to learn a lot of things before I could get going.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____11. I found the introduction power point informative.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____12. I could have flown just fine without the power point.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

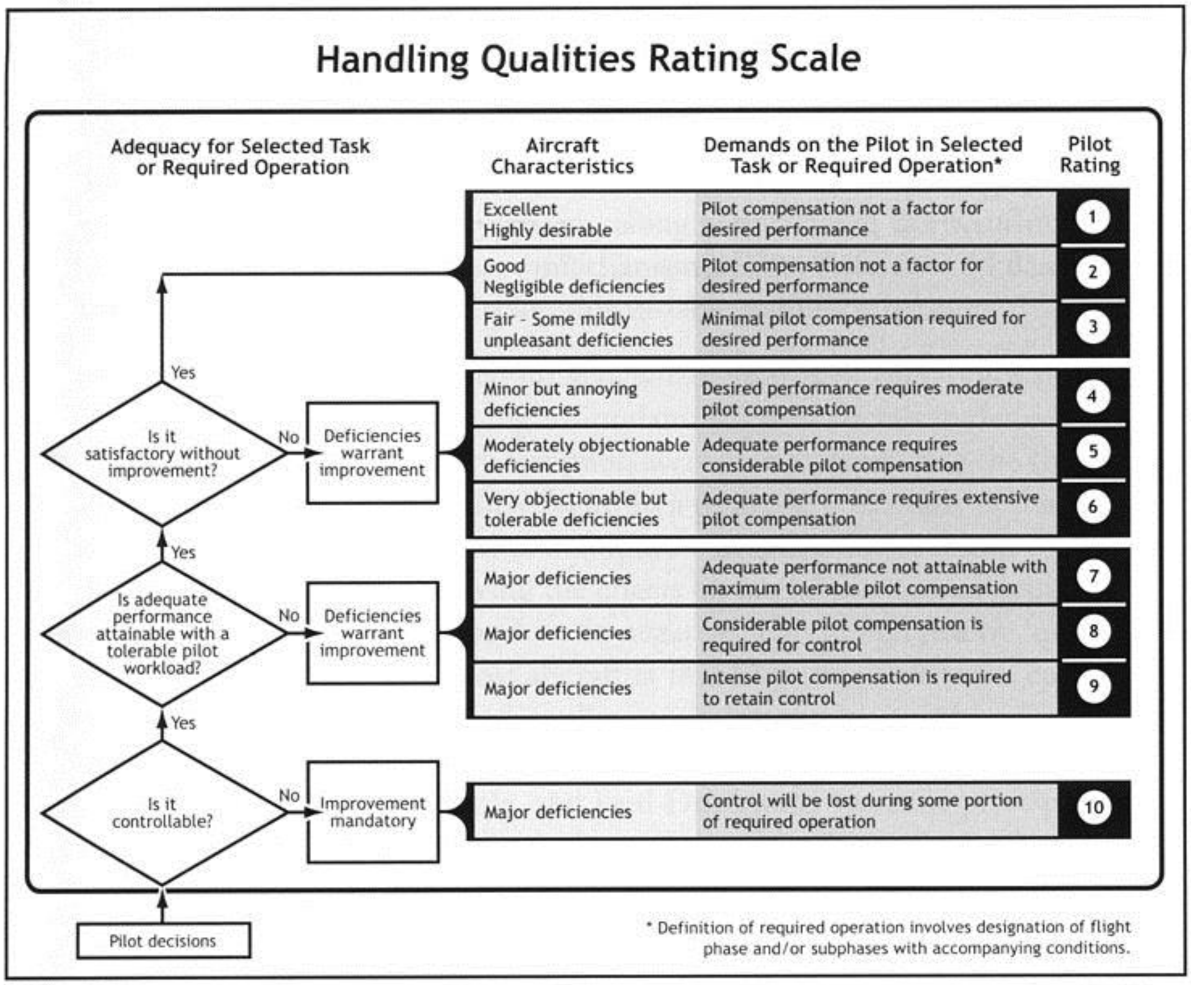
____13. I found the power point offered good tips for controlling the aircraft.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

____14. It was clear to me when I should shift.

1 - Disagree Strongly	2 - Disagree Slightly	3 - Neutral	4 - Agree Slightly	5 - Agree Strongly

C. Cooper-Harper Handling Qualities rating scale. Please ask for assistance if it is not clear as how to proceed.



D. Open-ended questions. Once again, there are no right answers and all answers are kept confidential so please answer truthfully and completely. If you need more room, simply ask for additional paper.

Would you recommend this to a friend? Why or why not?

If you were to rate your overall experience, what score would you give it out of 10?

What did you find most frustrating about your experience?

If you could change one thing about the way it is controlled, what would it be and why?

What did you like best about it? Why?

What did you like least about it? Why?

How can we improve the controls or the interface? Any ideas or suggestions are welcome.

Anything else you care to share or get off your chest?

Thank you for taking the time to complete the questionnaire. Your participation is appreciated.

APPENDIX C – PRE-FLIGHT TRAINING PRESENTATION FOR HF TESTING

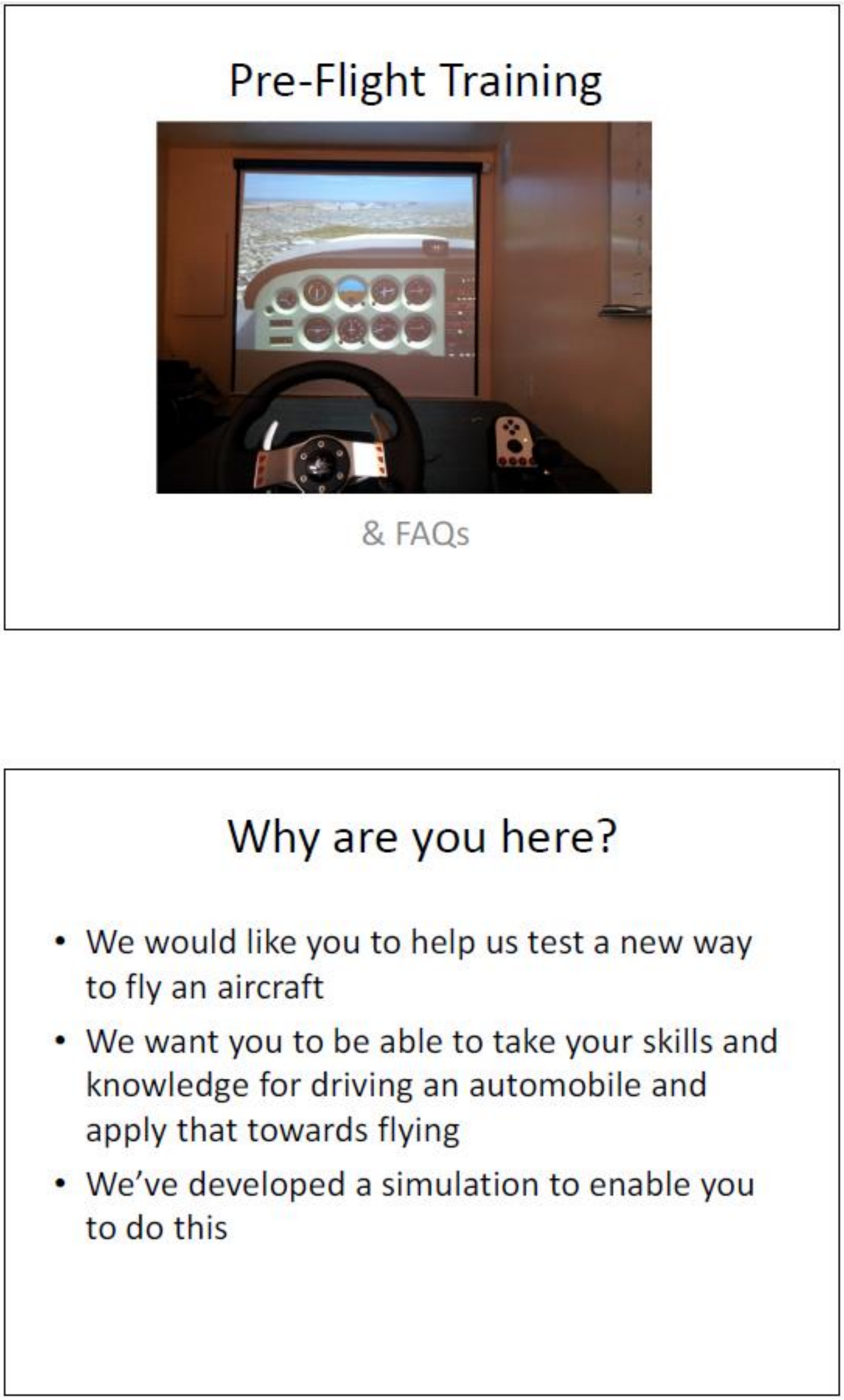


FIGURE 107: PAGES 1 & 2 OF PRE-FLIGHT TRAINING PRESENTATION

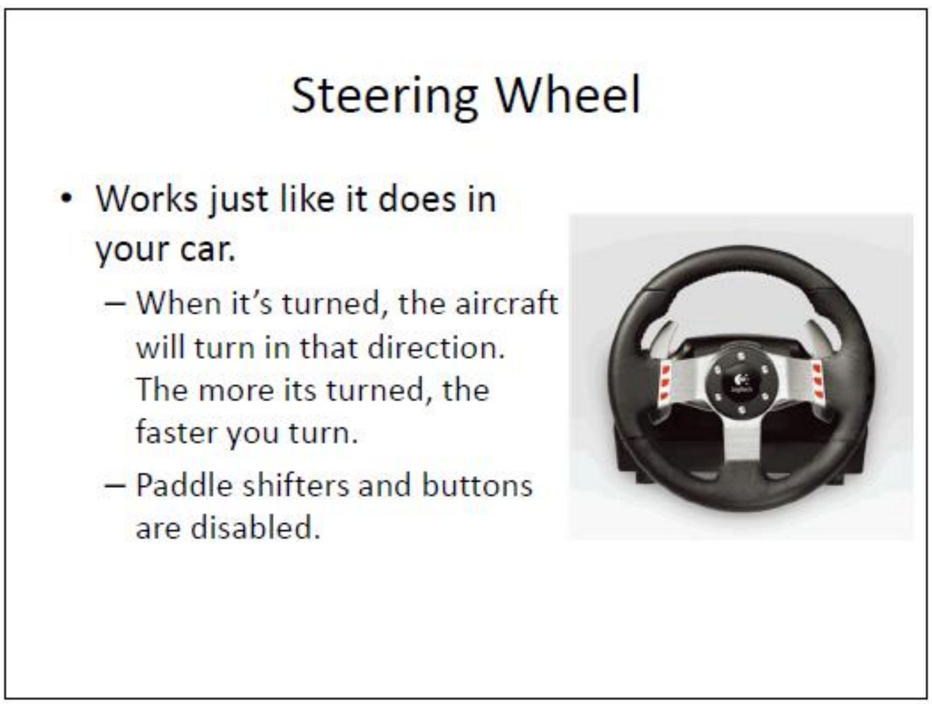


FIGURE 108: PAGES 3 & 4 OF PRE-FLIGHT TRAINING PRESENTATION

Gas, Brake, and Clutch Pedals

- The clutch pedal is disabled
  - Shifting is not like a car, you can just shift without clutch.
- Gas and brake pedal perform different functions depending on what “gear” you are in.
  - These will be explained.

6-Speed Shifter

- Has a typical layout
  - Shifting is not like a car, you can just shift without clutch.
- Each “gear,” aka flight mode will allow the aircraft to perform differently
  - Like climb, descend, cruise, etc.

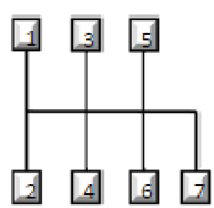
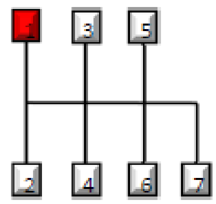


FIGURE 109: PAGES 5 & 6 OF PRE-FLIGHT TRAINING PRESENTATION

Takeoff Mode – "1st Gear"

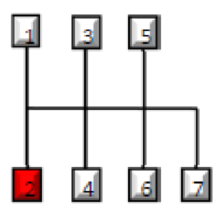
- Steering will let you steer on the ground
- Brake pedal – Held keeps engine at idle



- Gas pedal - held gives full power
- Once you are going fast enough, the plane will automatically take-off and begin to climb
- Once airborne and safely above the ground, shift into climb mode for more control.

Climb Mode – "2nd Gear"

- Steering will let you turn – must be held to continue turning
- Brake pedal – push to decrease rate of climb. Fully held will hold altitude.

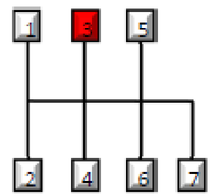


- Gas pedal – push to increase rate of climb. Fully held will climb as fast as possible.
- Once you reach your desired altitude, hold the brake pedal to maintain that altitude until shifting into low or high speed cruise.

FIGURE 110: PAGES 7 & 8 OF PRE-FLIGHT TRAINING PRESENTATION

Low Speed Cruise Mode – "3rd Gear"

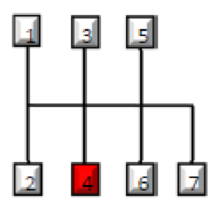
- Steering will let you turn – must be held to continue turning
- Brake pedal – push to decrease engine power (slow down)



- Gas pedal – push to increase power (speed up). Fully held will set power equal to high speed cruise. Shift to high speed to go faster.
- This mode is better for turning faster. *The slower the aircraft is going, the quicker you turn.*

High Speed Cruise Mode – "4th Gear"

- Steering will let you turn – must be held to continue turning
- Brake pedal – push to decrease engine power (slow down). Fully held will set power equal to low speed cruise.

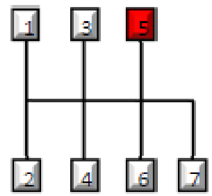


- Gas pedal – push to increase power (speed up). Fully held provides full power.
- This mode is better cruising in a straight line. If you're approaching a sharp turn, it would be wise to downshift to low speed cruise.

FIGURE 111: PAGES 9 & 10 OF PRE-FLIGHT TRAINING PRESENTATION

Descent Mode – “5th Gear”

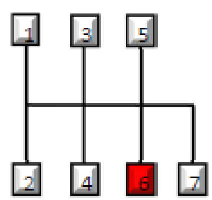
- Steering will let you turn – must be held to continue turning
- Brake pedal – push to decrease rate of descent. This will make you descend slower. Fully held will make the aircraft hold altitude.



- Gas pedal – push to increase rate of descent. Fully depressed will make you descend at a maximum rate.
- This mode is meant to let you descend during the flight if necessary, not for landing. To land, shift into landing mode.

Landing Mode – “6th Gear”

- Steering will let you turn – must be held to continue turning
- Brake pedal – push to decrease rate of descent. This will make you descend slower. Fully held will make the aircraft nearly hold altitude.

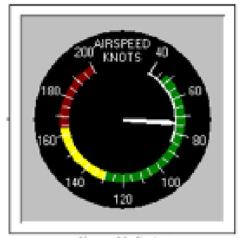


- Gas pedal – push to increase rate of descent. Fully depressed will make you descend at a maximum rate.
- Once you are lined up with the runway and are inside of the boxes, no gas or brake is required to land.

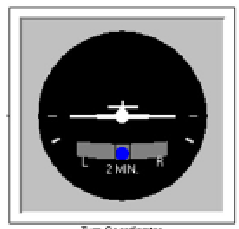
FIGURE 112: PAGES 11 & 12 OF PRE-FLIGHT TRAINING PRESENTATION

Instrument Descriptions

- Airspeed indicator – similar to a speedometer, it lets you know how fast you're going.
- Turn Coordinator – Allows you to see if you're maintaining altitude while turning.
  - If the ball stays in the center, then you're maintaining altitude.



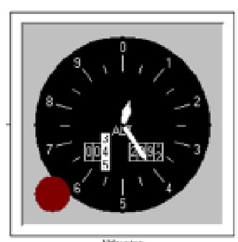
Airspeed Indicator



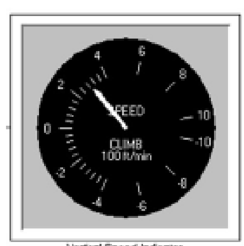
Turn Coordinator

Instrument Descriptions Cont'd

- Altimeter – Indicates what altitude you are at.
- Vertical Speed Indicator – Indicates your vertical speed in feet per minute. E.g. a vertical speed of 500 indicates that you'll climb 500 feet in one minute.



Altimeter

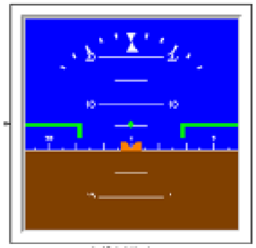


Vertical Speed Indicator

FIGURE 113: PAGES 13 & 14 OF PRE-FLIGHT TRAINING PRESENTATION

Instrument Descriptions Cont'd

- Artificial horizon – indicates what your pitch and bank attitudes are with respect to the horizon. Each pitch line is 2.5°. Each bank line is 10°.
- Heading Indicator – Indicates what your true heading is. North (0/360°), East (90°), South (180°), West (270°).



Artificial Horizon

Heading Indicator

Typical Operation

- You will begin the simulation on the runway ready for take-off in 1st gear and with your foot on the brake. When you're ready, press the gas pedal all the way for full power. Once you are going fast enough, you will automatically take-off and begin to climb.
- Once you are far enough away from the ground, you may shift into climb mode (2nd gear) to have more control over your rate of climb.
- Once you reach your desired altitude, apply the brakes to maintain that altitude until you shift into low or high speed cruise.

FIGURE 114: PAGES 15 & 16 OF PRE-FLIGHT TRAINING PRESENTATION

Typical Operation Cont'd

- If there's a turn coming up, it is recommended to use low speed cruise (3rd gear) until you will be flying straight for a while, then you may shift into high speed cruise (4th gear). If you need to turn more sharply, slow down by using the brake.
- Once you're cruising just be sure to stay on track by flying through the red boxes. You should only have to make small adjustments with the steering wheel similar to driving on a highway.
- If there is a sharp turn coming up it is recommended that you brake or downshift to low speed cruise.

Typical Operation Cont'd

- If you are required to descend before the boxes descend all the way down to the runway on the ground, you will want to use descent mode (5th gear).
- This will allow you to have more control over your descent rate if you choose to descend faster.
- Once you are at your desired altitude, use the brake to maintain that altitude until you shift back into low or high speed cruise mode.

FIGURE 115: PAGES 17 & 18 OF PRE-FLIGHT TRAINING PRESENTATION

Typical Operation Cont'd

- Once the runway is in sight and your "highway" (red boxes) begin descending all the way to the ground, it is time to shift into landing mode (6th gear).
- If you shift at the right time (as soon as the boxes start descending), you won't need to use the gas or brake to make any adjustments in order to landing, only steering to make sure you're lined up.
- If you're above the boxes, use the gas to descend faster and get inside. Conversely if you're below them, use the brake to descend slower and get inside. Once inside, just steer to stay lined up to land.

Typical Operation Cont'd

- The landing will become automated so as long as you're lined up with the runway and inside of the boxes, you've done your job successfully and will make it home in time for dinner.

FIGURE 116: PAGES 19 & 20 OF PRE-FLIGHT TRAINING PRESENTATION